

The Exocomets of β Pictoris: A study of exocometary dynamics

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Abstract

β Pictoris is a nearby, young planetary system hosting an edge-on oriented dust disk. It is not only the system where the first exocomets were discovered, but also the most studied exocomet system. Decades of observations since the first exocomet discovery in the 1980's have shown spectroscopic transits of evaporating exocomets at close orbital distances to the host star. Although many observational and theoretical studies have been carried out since discovery of the β Pictoris exocomet phenomenon, the physical nature and origins of these exocomets remain poorly understood. The aim of this thesis is to, through N-body simulations and theoretical modeling, relate to exocometary observations, determine likely regions of exocomet origin in the system as well as plausible mechanisms that drive the creation of the exocomets observed in β Pictoris. This work presents a simulation where the β Pictoris system was integrated together with a disk of over 100 thousand test-particles for 25 Myr, longer than the estimated age of the system. The simulation resolves close encounters between the simulated test-particles and the two planets of the system, as it uses the non-symplectic REBOUND integrator IAS15.

The results show that the system is generally highly dynamically unstable on short time-scales. Most of the test-particles initiated below ~ 35 AU are removed from the simulation, while the system is stable beyond this limit as the planetary perturbations have not yet reached this distance after 25 Myr. The simulation revealed additional regions of stability, one interior to the orbit of β Pictoris c and another region outside of the orbits of the planets, distributed in smaller semi-major axis ranges of stability between 20 and 25 AU. The results presented in this thesis show that exocomets can be sourced from these two regions of stability, as well as the inner edge of the ~ 35 AU stability region, at time-scales that are on the order of the age of the system. Exocomets are produced from two main regions of the β Pictoris system, the region interior to the planetary orbits and the region exterior to the orbits of the planets.

This thesis proposes that the two populations of exocomets, sourced from the two identified regions of stability, could correspond to the two families of exocomets observed spectroscopically in β Pictoris. The inner population exocomets are in the simulation created by eccentricity excitation through resonant interactions with β Pictoris c, resulting in a narrow distribution of radial velocities similar to one of the observed exocomet families. A broad radial velocity distribution is obtained for the exocomets of the outer population who are driven into the vicinity of the star through disruption by the two planets. This population could correspond to the second observed exocomet family. The outer population exocomets originate from outside of the water sublimation limit of the system and are efficiently transported from this region onto stargazing orbits. Compositional differences of the exocomets from the two populations are therefore expected. This work predicts that a fraction of the exocomets observed in β Pictoris today could have a significant, unseen, volatile content. A portion of the results presented here have also been published in [Jaworska & Hoeijmakers \(2026\)](#).

Additionally to the simulations, modeling of the sublimated exocometary material was performed in this study. This modeling found that the dynamical properties of ions in the gas released by exocomets could explain why certain elements are observed much more commonly than others. In particular, the recently discovered neutral sodium was found to strongly be affected by radiation pressure and have a short ionization time, making it unobservable at short distances to the star, where exocomets are expected. Neutral sodium could become observable on occasions where mechanisms such as fragmentation of the exocometary nucleus and/or exceptionally high electron density are present.

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Populärvetenskaplig Sammanfattning

Beta Pictoris (β Pic) är ett ungt och närbelagt stjärnsystem. Systemet består av en stjärna som är nästan dubbelt så tung som solen, omgiven av två Jupiter-liknande planeter samt en utbredd disk av stoft. Beta Pictoris är systemet där exokometer upptäcktes för första gången någonsin. Exokometer är små kroppar som utsöndrar stora mängder gas när de passerar tillräckligt nära sin stjärna. De observerades här redan för drygt 40 år sedan och trots tusentals observationer är det än idag många frågor som kvarstår om dessa kroppar. Det är idag fortfarande oklart vart exokometerna i Beta Pictoris härstammar från och vad det innebär för deras komposition. Kometerna i vårt solsystem härstammar från de kalla och avlägsna delarna av solsystemet och är uppbyggda av både is och sten. I de inre och varmare delarna av solsystemet finns bälten av asteroider, små kroppar som i största del består av sten. Genom att hitta möjliga exokomet-bälten i Beta Pictoris vill denna studien ta reda på i hur stor grad exokometerna där är lika de små himlakropparna, kometerna och asteroiderna, vi har i vårt egna solsystem.

I den här studien har en datorsimulering av Beta Pictoris utförts för att försöka identifiera vilka regioner i systemet som kan vara potentiella hem för de observerade exokometerna. Simuleringen visar att majoriteten av systemet är instabilt på grund av den starka gravitationen från de två planeter. Resultaten pekar på att det kan finnas två potentiella platser i systemet där exokometerna skulle kunna ha sitt ursprung. De skulle kunna härstamma från systemets yttre, kalla regioner och då vara snöbollsliknande som kometerna i vårt solsystem. Exokometerna kan också ha sina rötter i den mycket varma inre regionen av systemet och då vara mer lika solsystemets asteroider. Kortfattat visar simuleringen att det finns en möjlighet att Beta Pictoris har små himlakroppar som både är lika kometer och asteroider och på så sätt är systemet likt vårt solsystem.

Observationer har tidigare visat att exokometerna i Beta Pictoris är indelade i två familjer med olika egenskaper. Genom att jämföra egenskaper av de observerade exokometerna och resultat av datorsimuleringen kan denna studien säga att de två familjerna möjligen härstammar från olika platser i stjärnsystemet. Detta är första gången som de två exokometfamiljerna kunnat förklaras med hjälp av simuleringar.

Denna avhandling undersöker även varför vissa grundämnen observeras oftare än andra i exokometerna. När exokometer observeras är det oftast inte själva kroppen som ger upphov till signalen. När exokometen kommer tillräckligt nära stjärnan, utsöndras stora mängder gas som täcker en tillräckligt stor del av stjärnan för att vara synlig för observationerna. Resultaten av denna studie visar att det starka ljuset från stjärnan bidrar till att neutrala ämnen i gasen blir osynliga. Neutrala atomer fångar upp det energirika ljuset och som konsekvens förlorar de elektroner och blir positivt laddade joner, en process kallad jonisering. På grund av att ljuset från stjärnan är starkt, går joniseringsprocessen fort och ämnen som natrium hinner inte expandera för att kunna täcka tillräckligt mycket av stjärnan och kunna observeras. Natrium observeras bara i speciella fall där det starka joniserande ljuset från stjärnan kan motverkas av andra processer.

Chapter 1

Introduction

A planetary system is born from the gravitational collapse of a molecular cloud (Safronov, 1972). Firstly, a protostar is formed at the center of the collapse and is surrounded by a disk that is mostly gaseous, while a small percentage consists of dust grains. These dust grains coagulate and form larger bodies, eventually growing into planets which emerge out of the gaseous disk. The planets will continue growing by accreting solids and gas from the proto-planetary disk (Pollack et al., 1996). Planet formation remains active in the system for as long as the disk remains gaseous; this typically lasts a few Myr (Williams & Cieza, 2011). After the depletion of the primary gaseous proto-planetary disk, a secondary disk can emerge from collisional grinding of larger planetesimals (Wyatt, 2008). Such secondary disks are called *debris disks* and have been detected around numerous stars. This has historically been done by observing whether a star exhibits an excess of infrared radiation, which is produced by the re-emission in infrared wavelengths of starlight by dust grains that make up the disk. As dust grains can be efficiently removed by radiation pressure, an observation of infrared excess implies that collisional grinding is ongoing, and that larger bodies must still be present, even if they cannot be observed directly (Krivov, 2010). Millions of stars have been reported to have an infrared excess. Among them, different morphologies and structures of dust disks have been detected. The sub-structures of dust disks such as cavities, warps and asymmetries can provide clues about undetected planets present in the disk (Hughes et al., 2018).

A circumstellar debris disk oriented edge-on to the line of sight was observed in 1984 in the β Pictoris (β Pic) system (Smith & Terrile, 1984; Aumann, 1985) using the Infrared Astronomy Satellite (IRAS; Neugebauer et al. 1984). The disk was directly imaged by ADONIS instrument (Beuzit et al., 1994) on ESO’s 3.6 m telescope, see Fig. 1.1. β Pic gained a significant amount of attention as the disk was observed to be warped (Burrows et al., 1995) and asymmetric (Telesco et al., 2005) possibly due to the gravitational effect of unseen planets. Today, the presence of two giant planets in the system has been confirmed. The first planet, β Pic b, was discovered through direct high contrast direct imaging (Lagrange et al., 2009; Lagrange et al., 2010) see Fig. 1.1 again. A second planet, β Pic c, was later discovered by measuring fluctuations in the radial velocity of the star Lagrange et al. (2019).

Additionally to the debris disk and the planets, observations of β Pic show spectral time-variability in several different elemental lines of absorption features that are Doppler-shifted by tens-to-hundreds of km/s away from the central wavelengths of the corresponding stellar lines. Ferlet et al. (1987) were the first study to attribute the variability to absorption by transiting gas released from comet-like bodies. These bodies are called *exocomets*. Exocomets are planetesimals which could either be icy or rocky, that evaporate material as they transit the line of sight on a short distance from the star. They provide a unique opportunity of observing otherwise invisible planetesimals and therefore provide a bridge in the gap between debris disks, late-stage planet formation and exoplanetary composition in order to form a better understanding of the formation and evolution of planetary systems. Since their initial discovery almost 40 years ago, thousands of exocometary events have been observed in β Pic (e.g Ferlet et al., 1987; Kiefer et al., 2014); however, their properties are still largely a mystery.

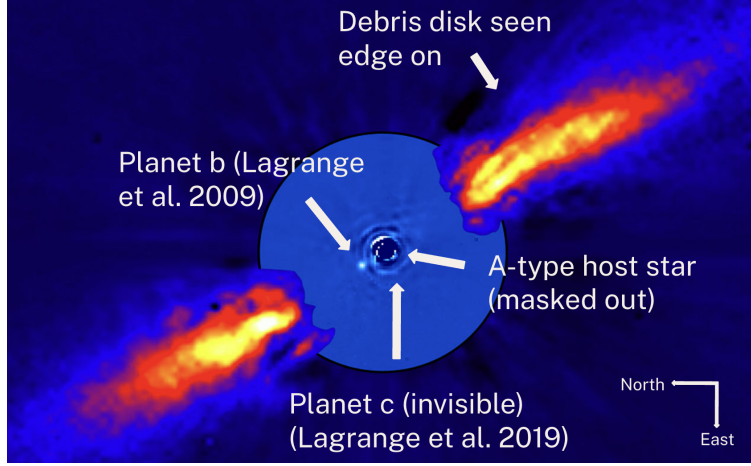


Figure 1.1: β Pictoris directly imaged in infra red light. The light from the bright host star has been masked out, allowing for a higher contrast and faint features to become visible. The red flares extending towards the upper right and lower left corners of the figure are due to light reflected by the edge-on circumstellar debris disk, detected due to infra red excess already in the 1980’s. One of the system’s two know planets, β Pic b is visible in the figure. The figure is a result of two direct observations, the outer system (featuring the disk) was observed with the ADONIS instrument (Beuzit et al., 1994) on ESO’s 3.6 m telescope while the inner system (featuring β Pic b) was observed with the NACO instrument (Lenzen et al., 2003; Rousset et al., 2003) on the Very Large Telescope. Figure credit: ESO/A.-M. Lagrange et al, adapted.

One of the unresolved mysteries about the β Pic exocomets is their origin. Past studies have assumed that these bodies are similar to solar-system comets and thus are predominantly composed out of volatile ices (Kiefer et al., 2014). However, among the 13 atomic species observed in β Pic exocomets only one volatile species, carbon, has ever been detected (Iglesias et al., 2025). This poses a question of whether the lack of observations of expected volatiles is caused by observational biases, as key volatile tracers often have transitions outside the observed wavelength range, produce weak spectral signatures (Kenworthy et al., 2025), and may be rapidly photoionized in the vicinity of β Pic (Fernández et al., 2006), or simply that the exocomets in β Pic are primordially devolatilized and therefore better resemble solar system asteroids rather than icy comets.

Another unanswered question about the exocomets in β Pic is how they dynamically evolve onto trajectories that bring them into a close vicinity of the star. Spectroscopic observations of the variable absorption created by exocomets show that there is a asymmetry in the radial velocity distribution of the observed exocomet events. The majority of the β Pic exocomets are observed to have a positive radial velocity, they are mostly red-shifted and thus falling toward the star. This property has earned the exocomets of β Pic an additional name *Falling Evaporating Bodies* (FEBs) which was used before the term exocomets became widely accepted in the field. Several creation mechanisms that could explain this asymmetry have been proposed and the most popular theory is that resonant interactions with the planets are responsible for the creation of exocomets in β Pic. Resonant interactions would excite the orbits of a population of planetesimals in the same direction, yielding a population of exocomets on orbits with aligned periastra. The observed radial velocity of these exocomets would thus have a narrow distribution, centered on a radial velocity that depends on the orientation of this alignment with respect to the line of sight, possibly explaining the asymmetry (Beust & Morbidelli, 1996).

In attempts to propose answers to the questions left unanswered by observations, dynamical N-body simulations of the have been performed recently by Rodet & Lai (2024) and Beust et al. (2024). They set up the β Pic system using observationally measured parameters of the star and planets, together with a disk of test-particles that model planetesimals. The system was simulated for 10 Myr, a time-scale corresponding to

half of the system’s estimated age, and potential regions which are dynamically stable on such a time-scale are sought after. These regions could be potential exocomet reservoirs: regions where exocomets in β Pic could be sourced from at the present time. [Rodet & Lai \(2024\)](#) used a computationally expensive but highly accurate non-symplectic integrator but included a number of test-particles that was too small to resolve details of the system. They were able to show that particles are efficiently scattered onto stargrazing orbits but did not make any predictions for present-day exocomet observations. [Beust et al. \(2024\)](#) included a significantly larger amount of test-particles in their simulations owing to their use of a symplectic integrator. They could successfully identify one region at an orbital distance of ~ 1 AU from the star, that could be a potential exocomet reservoir, where exocomets are susceptible to excitation via the mean motion resonance with the system’s innermost planet, β Pic c.

An important property of the β Pic exocomets which is yet to be explained by simulations and theoretical studies was discovered by [Kiefer et al. \(2014\)](#) upon an analysis of eight years of archival spectroscopic observations of β Pic. They were able to determine that the exocometary events in the system can be divided into two different, distinct populations of exocomets. These two populations exhibit different spectral properties such as absorption depths and distribution of radial velocities in transit. It is however still unclear whether the two families are sourced from the same exocomet reservoir and where in the system such a reservoir or reservoirs should be expected. Furthermore, it remains unknown if the mechanisms driving the creation of exocomets in β Pic are the same for the two populations and if these mechanisms could explain the differences in observed properties. Predictions made by the simulations of [Beust et al. \(2024\)](#) could explain one of the exocomet populations well, yet no theoretical study has predicted two different populations of exocomets in β Pic.

In this thesis, I aim to perform dynamical simulations of the β Pic system together with a disk of planetesimals to try to explain decades of exocomet observations in the system. In particular, the simulations presented in this work attempt constraining creation mechanisms, origins and compositions of these bodies. I aim to combine the use of a large amount of test-particles, comparable to [Beust et al. \(2024\)](#), with the use of an accurate non-symplectic integrator as used by [Rodet & Lai \(2024\)](#), namely the IAS15 integrator ([Rein & Spiegel, 2015](#)) which is part of the REBOUND N-body code ([Rein & Liu, 2012](#)). This integrator is more suitable for simulating the dynamical evolution of exocomets as it resolves highly eccentric orbits and close encounters.

Additionally to N-body simulations, in order to accurately interpret exocomet observations the evaporated material itself needs to be modeled. The observations are possible due to gas and dust released by the exocomet absorbing stellar light. Therefore to accurately relate simulations to observations an additional model of the behavior of evaporated material is required. Through such modeling, I aim to find clues to the reason behind differences in observed properties of absorption in different elements (e.g. [Beust et al., 1989](#); [Hoeijmakers et al., 2025](#)).

Chapter 2

Theoretical Background

This work aims to use dynamical modeling to understand the properties of exocomets observed in β Pic. This chapter provides the theoretical background necessary for the interpretation of the methodology and results of this thesis, as well as putting this work into the context of previous studies. As a majority of the dynamical modeling presented in this thesis relies on orbital dynamics, their fundamentals are introduced in [Sect. 2.1](#). Exoplanet detection methods are reviewed in [Sect. 2.2](#) as these provide a basis for the project. Exocomet detection methods are discussed in [Sect. 2.3](#) where the concept of exocomets is introduced and put into a historical context. The β Pic system is introduced in [Sect. 2.4](#), where additionally a deeper understanding about the exocomet phenomenon of β Pic is formed. Finally, an overview of the important theoretical background for the modeling of sublimated exocometary material is presented in [Sect. 2.5](#).

2.1 Orbital Dynamics

Two massive bodies will experience a mutual gravitational attraction as defined by Newton’s law of universal acceleration:

$$F = G \frac{m_1 m_2}{r^2}, \quad (2.1)$$

where G is the gravitational constant, m_1 and m_2 are the masses of the two bodies and r is the distance between them. A system of two bodies is often referred to as the *two-body problem*. As the bodies move further away from each other, the attractive gravitational force will get smaller. The mutual gravitational attraction will cause the bodies to move relative to each other. If the total energy of the two-body system is negative, the bodies will be gravitationally bound to each other and their movements can be explained by elliptic *orbits* around a common center of gravity. As a result, their mutual distance varies periodically as a function of time. An elliptic orbit is defined by a set of six orbital parameters ($a, e, i, \Omega, \omega, f$) they are listed and explained below, see [Fig. 2.1](#) for a visual representation.

- a - Semi-major axis: Often used to define the distance between the two bodies. It is half of the major axis (longest axis) of the ellipse.
- e - Eccentricity: A parameter that quantifies the shape of the orbit. For a fully circular orbit, the eccentricity is defined as $e = 0$. A more elongated, more elliptic orbit will have a higher eccentricity. Eccentricity is defined such that bound orbits must have $e < 1$.
- i - Inclination: The angle between the orbital plane and a reference plane.
- Ω - Longitude of ascending node: The angle between a reference direction (zero point of longitude) and the direction of the orbit’s ascending node. The ascending node is the intersection between the orbital plane and the reference plane, where the body passes upward through the plane. The longitude of ascending node describes the rotation of the orbit.
- ω - Argument of periapsis: The angle between the ascending node and periapsis. The periapsis is the point in the orbit where the orbiting body is the closest to the center of mass. The argument of periapsis

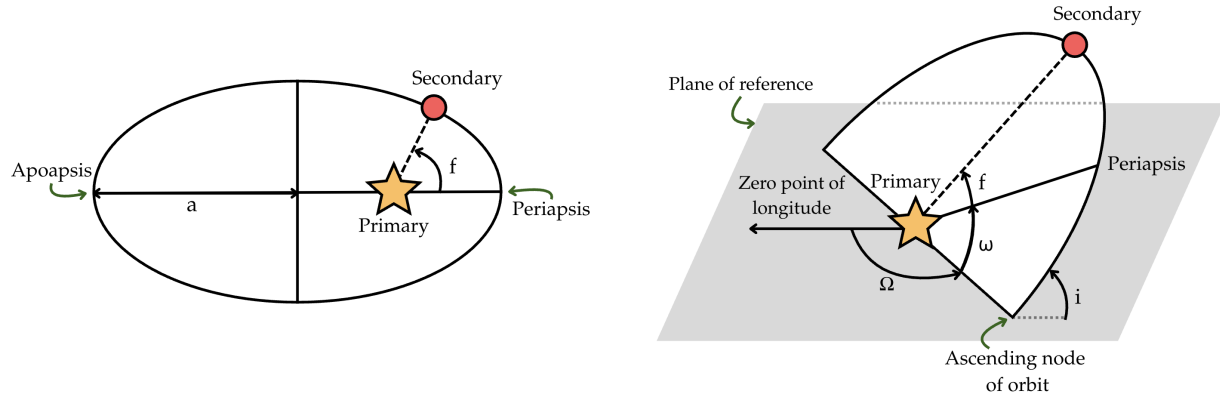


Figure 2.1: Schematic of the geometry of an elliptic orbit, explaining the definition of orbital parameters. **Left panel:** A top-view of an orbit, the primary object being in one of the focus points of the ellipse. The point in the orbit where the distance between the primary and secondary is smallest, periapsis is indicated together with apoapsis where this distance is the largest. **Right panel:** A three dimensional schematic of the geometry, indicating a reference plane and an orbital plane.

describes the rotation of the orbit, similarly to Ω . If $i = 0$ the angles ω and Ω are in the same plane and can simply be added together, see Fig. 2.1.

f - True Anomaly: The angle between periapsis and the instantaneous position of the body in the orbit defined by the orbital parameters listed above, as a function of time

The point in the orbit where the secondary approaches closest to the primary is called *periapsis* $r_{\text{peri}} = a(1-e)$ whereas the point in the orbit where the two bodies are the furthest apart is called *apoapsis* $r_{\text{apo}} = a(1+e)$. The sum of the argument of periapsis and longitude of ascending node is called the *longitude of periapsis* $\varpi = \Omega + \omega$ (de Pater & Lissauer, 2015).

An example of the two-body problem is a system of a star and a planet for which the Kepler's laws of planetary motion are defined. These laws can be applied to any system of two massive bodies. The first law describes the distance r between the star and the planet that orbits around it:

$$r = \frac{a(1-e^2)}{1+e\cos f}. \quad (2.2)$$

Note that since the orbit is elliptic this distance will vary depending on the true anomaly f , so depending on time see Fig. 2.1 (de Pater & Lissauer, 2015). In the case of a body orbiting around a star, the closest and furthest approach are called periastron and apastron respectively.

A secondary body orbiting a primary will often have a rotation around its own axis. Let us consider a system of a star and a planet. The Earth for example has a 24 hour long rotation period around its own axis. The *obliquity*, also called axial tilt, is the angle between the planet's plane of rotation around its own axis and the plane of its orbit de Pater & Lissauer (2015).

2.1.1 Perturbations and Mean-Motion Resonance

Most planetary systems, even systems hosting two planets or more, can be treated as two-body problems. The planets are significantly less massive than the primary star however they still do exert small perturbations

on each other, which result in deviations from the Keplerian two-body orbit. Even though the perturbations are small in comparison to the dominant force exerted by the star, over time they add-up and can have a significant effect on the orbital evolution of the planets. This is due to the fact that planets move periodically and they will exert small perturbations every time they pass each other in the same configuration. If the frequency of these perturbations is close to or equal to the natural orbital frequency of the other planet, the planets are near *resonance* (de Pater & Lissauer, 2015). Their orbital periods form a ratio of small integers. Resonance is also possible for other bodies such as moons and asteroids.

Two bodies can be in *mean motion resonance* (MMR) if their orbits satisfy a combination of orbital elements given by the *critical argument* σ . For a body in a (p+q):p resonance with a planet this is described by:

$$\sigma = (p + q)\lambda_{\text{planet}} - p\lambda_{\text{body}} - q\varpi_{\text{body}}, \quad (2.3)$$

where ϖ is the longitude of periapsis and $\lambda = \varpi + M$ is the mean longitude, it depends on the mean anomaly M which is an angular variable that increases uniformly with time (Yoshikawa, 1989). When a body is trapped in a MMR, σ oscillates around an angle, this is called *libration*. The center of libration depends on the resonance and can be around an angle between 0° and 180° . For example the Hilda asteroids which are in a 3:2 MMR with Jupiter have a libration of $\sigma \approx 0^\circ$, thus when the asteroids are in conjunction with Jupiter, so when $\lambda_{\text{planet}} = \lambda_{\text{body}}$ the asteroids are close to their perihelion, far away from Jupiter. Therefore, the 3:2 resonance provides a protection to the Hilda asteroids as they avoid close encounters with Jupiter and is thus a stabilizing resonance (de Pater & Lissauer, 2015). Note that the 3:2 MMR does not necessarily always librate around 0° . In many resonances, the critical argument librates about 0° or 180° and the libration center is determined such that the minor body never is at its apapsis when $\lambda_{\text{planet}} = \lambda_{\text{body}}$, so that it avoids close encounters with the planet (Yoshikawa, 1989). A libration around 0° is an exact resonance while a libration around 180° is called an *apastric resonance* (Murray & Dermott, 1999).

A classic example of MMR are the moons of Jupiter, which are stabilized by the resonance. The moon Europa has an orbital period that is twice as long as the orbital period of Io, placing Europa in a 2:1 resonance with Io. Ganymede's orbit around Jupiter is four times as long and is therefore in a 4:1 resonance with Io. An example of resonances acting as de-stabilizing mechanisms is found in the pattern of the asteroid belt, the so-called Kirkwood gaps which appear at the 4:1, 3:1, 5:2, 7:3 and 2:1 resonances with Jupiter (Moons, 1996). Due to the resonant perturbations from Jupiter, asteroids on orbital periods that are related to the orbit of Jupiter with an integer ratio are dynamically excited their eccentricities and/or inclinations grow resulting in a clearing of asteroids at the orbital distances corresponding to the resonances (de Pater & Lissauer, 2015). Yoshikawa (1989) investigated the MMR effect on simulated asteroids in the asteroid belt and found that the eccentricities of asteroids in resonances that correspond to the Kirkwood gaps grow on a short time-scale. In most resonances, the simulated asteroids obtained an eccentricity larger than 0.4 in under 10^5 years while the eccentricities of asteroids in the 4:1 resonance grew up to almost 1 as a result of the MMR with Jupiter.

Secular resonances occur when the precessions of two orbits align with each other. An example of such a resonance is the v_6 resonance in the solar system. It occurs when the frequency of precession of the longitude of perihelion of an asteroid g matches the secular frequency g_6 , the mode that dominates perihelion precession of Saturn, so when the condition $v_6 = g - g_6 = 0$ is satisfied. The orbits of asteroids are excited and their eccentricity grows high enough for them to cross into the inner solar system and the vicinity of the Sun (Beust & Morbidelli, 1996).

2.1.2 The Hill Sphere

A particle moving in a system of more than 2 bodies will experience a gravitational attraction from all of the bodies in the system. Depending on the location of this particle, different bodies will dominate the total force felt by the particle. As explained above, in the majority of the possible positions in the system, the primary object, such as the star in a planetary system, will exert the dominant force on the particle, while secondary bodies, such as planets, will contribute with perturbations. However if the particle at any time is located close enough to a secondary body, the force on this particle will be dominated by the gravitational

interaction from the less massive secondary body. There is a spatial boundary around each secondary body in the system, within which the gravitational acceleration felt by a particle is dominated by the gravity of the secondary. This sphere of influence is called the *Hill sphere*. Outside of the Hill sphere, the gravitational potential in the frame co-rotating with the secondary is dominated by the primary. The equation defining the radius of the Hill sphere is:

$$R_H = a \left(\frac{m}{3(m+M)} \right)^{1/3}, \quad (2.4)$$

where m is the mass of the secondary body and M is the mass of the primary body (Hill, 1878; Murray & Dermott, 1999). The Hill sphere around the secondary is smaller if the mass ratio m/M is smaller, so for example a giant planet orbiting around a light star will have a larger Hill sphere compared to a terrestrial planet orbiting a massive star. The radius of the Hill sphere also depends on the semi-major axis, a . The Hill sphere of a secondary will be smaller if it has a smaller semi-major axis, that is if it orbits the primary at a shorter distance.

Inside the Hill sphere the gravitational potential of the secondary is deeper than that of the primary and therefore dominates over it. A third particle could be captured by a secondary body, if this particle cannot escape the potential well created by the secondary body, see Eq. (2.4) above. This is the case for moons that are found residing deep inside planetary Hill spheres. Once a particle is close enough to the secondary such that it lacks the kinetic energy to overcome the potential barrier caused by the mass of the secondary body, it will reside inside the Hill sphere and become a satellite of the secondary.

2.2 Observing Exoplanets

The first exoplanet around a main-sequence star was detected in 1995 by Mayor & Queloz (1995). This discovery was deemed so important that it earned a part in the 2019 Nobel prize in physics. A little over 30 years later, thousands of exoplanets are confirmed. Their details, such as atmospheric composition, are now being studied to gain valuable knowledge about the formation and evolution of planetary systems. The first exoplanets were primarily detected using the radial velocity (RV) method described in Sect. 2.2.1, however as the hunt for exoplanets expanded the transit method was shown to be more effective at finding exoplanets. The majority of the confirmed exoplanets were discovered using the transit method, which is discussed in Sect. 2.2.2. The last exoplanet discovery method reviewed here is direct imaging, presented in Sect. 2.2.3.

2.2.1 The Radial Velocity Method

The radial velocity (RV) method is an indirect way of detecting exoplanets around stars. It makes use of the Doppler-shift experienced by light emitted by a body moving along the direction of the line of sight, a body that has a radial velocity. The Doppler-shift is defined as:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_r}{c}, \quad (2.5)$$

where v_r is the radial velocity, c is the speed of light, λ_0 is the wavelength at rest (when $v_r = 0$) and λ is the observed, Doppler-shifted wavelength (Kitchin, 1995). If an observed star is hosting a planet, the two bodies will orbit around a common center of mass. The star will thus be observed to "wobble", the light observed will be Doppler-shifted to a different degree as a function of time. This can be detected by looking at the stellar spectrum, see left panel of Fig. 2.2. As the star moves away from the observer, its light will be red-shifted away from the rest wavelength λ_0 and the spectral lines will move to longer wavelengths. As the star moves toward the observer, the light will instead be blue-shifted to shorter wavelengths. If the planet has a small mass compared to the mass of the star, the center of mass will be located very close to the center of the star and thus the star will not have a pronounced movement. More massive planets will exert a larger pull on the star and the common center of mass will be located further away from the center of the star, causing a larger radial velocity shift. Therefore, it is easier to detect massive planets around low-mass stars with the RV method. Additionally, the RV fluctuations of the host star will also be affected by the orbital semi-major

axis of the planet. Planets on close-in orbits will have a greater effect on the dislocation of center of mass. Therefore, the RV method is also biased toward detecting planets on short orbits (de Pater & Lissauer, 2015).

Since the amplitude of the RV fluctuations of the host star is sensitive to the mass of the planetary companion, the RV method can be used to find the absolute mass of the planet $m_p \sin i$. This is the minimum mass of the planet, not the true mass m_p which is not possible to constrain as it is degenerate with the inclination of the orbit, the RV amplitude of a star hosting a very massive planet on a highly inclined orbit will be smaller than if the orbit was in the plane of the line of sight. The RV method can also be used to find the orbital elements of the planetary orbit by studying the RV fluctuations over time, the so called RV-curve. From the periodicity of the RV-curve the period of the orbit can be found and therefore also the semi-major axis. The shape of the RV-curve is also important. In a circular orbit, the star experiences an equal gravitational pull from the planet at all times, meaning that for half of the orbit the stellar light will be red-shifted and for the other half blue-shifted. In an eccentric orbit however, the planet spends more time close to apastron than periastron. The host star experiences an uneven pull from the planet, resulting in an asymmetric RV-curve from which the eccentricity can be deduced. In a similar way, the shape of the RV-curve is affected by the orientation of the orbit and therefore also the argument of periastron, ω can be found using this method (Hatzes, 2016).

2.2.2 The Transit Method

The transit method of exoplanet detection and observation makes use of planets that are on orbits oriented in such a way that they cross the line of sight while covering a part of the stellar disk. This results in a dip in the observed stellar light, a transit light-curve (see the middle panel of Fig. 2.2). The transit depth is proportional to the square of the ratio between the radius of the planet and the radius of the star $(R_p/R_{\text{star}})^2$. A larger planet will cover up a bigger part of the stellar disk. The radius of the planet, R_p , can be found from the depth of the transit light-curve because as the planet-to-star size ratio increases, the amount of stellar light blocked by the planet increases and thus the transit depth increases. From the transit-light curve, the parameters of the planetary orbit can be found. The period and thus also the orbital semi-major axis can be found from the periodicity of the transit light-curve. The shape of the transit light-curve can be used to determine the inclination by using the impact parameter:

$$b = \frac{a}{R_{\text{star}}} \cos i, \quad (2.6)$$

where a is the semi-major axis, R_{star} is the radius of the star and i the inclination, note that this is valid for circular orbits. A partial transit occurs when $R_{\text{star}} + R_p > a \cos i > R_{\text{star}} - R_p$ and a full transit occurs when $a \cos i > R_{\text{star}} - R_p$ (Collier Cameron, 2016).

The transit method has also been used to characterize the atmospheres of exoplanets through transmission spectroscopy. As the planet transits in front of the star, stellar light will pass through its atmosphere which is not fully opaque. Depending on what species are present in the atmosphere, certain wavelengths of the light will be absorbed and contribute to a slightly deeper dip in the light-curve which will have different depths in different wavelength ranges. The extra absorption from the planet can be extracted from the spectrum of the star, often requiring techniques such as cross-correlation to extract the faint planetary signal (Snellen et al., 2010).

Note that the transit method only can detect planets that have impact parameters smaller than one, that is transiting planets. In reality, this requirement is satisfied for only a small sub-set of planetary systems. Non-transiting planets are therefore less likely to have radius and inclination estimates.

2.2.2.1 Limb-darkening

The transit method can also be used to estimate the limb darkening of the host star. When observing a star, the observed intensity will peak at the center of the stellar disk while the edges of the star, the limbs,

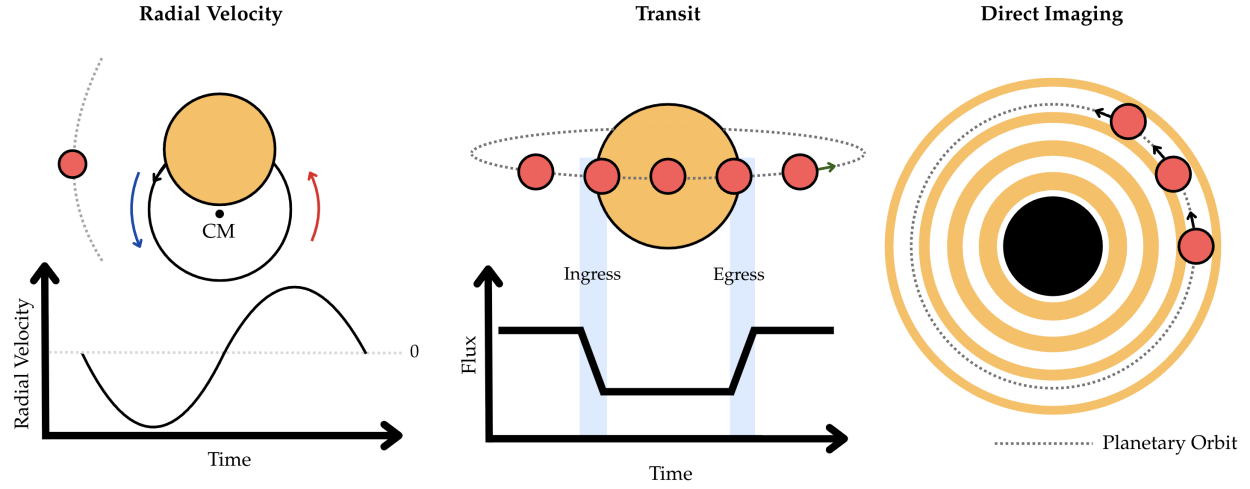


Figure 2.2: Schematics of three exoplanet detection methods. **Left panel:** The radial velocity method. The planet and the star orbit around a common center of mass (CM). When the star moves away from the observer, the lines in its spectrum are Doppler shifted to longer (bluer) wavelengths. As it moves toward the observer, the spectral lines are instead red-shifted. **Middle panel:** The transit method. As the planet transits in front of the star it will dim its light slightly resulting in a dip in the photometric light-curve. **Right panel:** The direct imaging method. The planet is imaged directly in IR-light which is made possible as the light from the star is blocked or masked out.

will appear darker. This effect is called the limb-darkening. At the center of the stellar disk the observation probes deeper layers of the star, as the star is viewed straight-on. Limb-darkening arises due to the fact that the limbs are observed at an angle γ , and the line of light cuts through the upper, cooler layers of the star. Observation probes higher levels of the star, as the optical depth limit is reached further up due to the longer path from the limb to the direction of the line of sight. Layers higher up in the star are generally cooler and emit less intensely, resulting in an apparent darkening at the stellar limbs (de Pater & Lissauer, 2015).

As a planet transits in front of the star, it will occult the limb first but as the planet moves in transit it will occult brighter and brighter parts of the star until it reaches the center of the stellar disk. As the intensity increases during the transit so will the depth of the transit light-curve, resulting in a light curve that is shallower at ingress (start of transit) and egress (end of transit) and deeper in the center. If the star had a uniform intensity, the transit would have a constant flat shape during transit (de Pater & Lissauer, 2015). Several different methods can be used to model the limb-darkening of stars. A popular method is to use the quadratic limb-darkening law where specific intensity of a star $I(\mu)$ is described as:

$$\frac{I(\mu)}{I(1)} = 1 - u_1 (1 - \mu) - u_2 (1 - \mu)^2, \quad (2.7)$$

where $\mu = \cos \gamma$ and γ is the angle between the line of sight and the emergent intensity, $I(1)$ is the specific intensity at the center of the disk and u_1 and u_2 are the quadratic limb-darkening coefficients which vary from star to star (e.g Claret, 2000; Kipping, 2016; de Mooij et al., 2017).

2.2.3 The Direct Imaging Method

The direct imaging method, is in contrast to the RV and transit methods discussed above, directly observing exoplanets. Images of the planet are taken over time as it moves in its orbit around the star, see right panel of Fig. 2.2. Direct imaging allows for the direct study of light reflected (optical) and emitted (infra-red) by the planet (Claudi, 2016). This is however complicated by the presence of the star which is located at a small

angular distance to the planet and is overwhelmingly much brighter. Due to the close location and brightness of the star, the contrast (brightness ratio between the planet and the star) is very small and planets are by themselves not resolvable. Their weak signal is lost in the stellar light. In order to reveal the planetary signal, the stellar light is subtracted such that the surroundings of the star can be revealed. The subtraction is complicated by the variable effects of the Earth's atmosphere and by the diffraction of the telescope. A coronagraph can be used to block out the peak of the stellar light, but residual light is still present after this, as can be seen in Fig. 2.2. Post-process techniques are then used to remove this excess light (Zurlo, 2026). Note that the exact methods of direct imaging and post-processing are not central to this thesis and thus details will not be covered here.

The direct imaging method is relying on the ability to resolve the planet as a point source of light next to the star. This is difficult due to the small separation of the two bodies. The resolving power of a telescope is determined by the diameter of its mirror, D as:

$$\theta_{\text{diff}} = 1.22 \frac{\lambda}{D}, \quad (2.8)$$

where λ is the wavelength of the light observed and θ_{diff} is the inner Airy disk of the diffraction pattern formed by the telescope. Even after the subtraction of the stellar light, the diffraction pattern caused by the telescope complicates the detection of a planet, this pattern is corrected for using post-processing techniques (Zurlo, 2026). The maximum angular separation between a planet and its host star is:

$$\theta = \frac{a(1+e)}{d}, \quad (2.9)$$

where a and e are the semi-major axis and eccentricity of the planetary orbit and d is the distance from the system to Earth (Claudi, 2016). A smaller resolving power is needed to detect planets on wide orbits that are in systems close to Earth but in order to resolve planets in systems located further away and/or on shorter orbits, a larger telescope mirror is needed.

The small angular separation is not the only challenge for direct imaging of exoplanets. The other, significant issue is the fact that the star is several orders of magnitude brighter than the planet, the planet-to-star flux ratio, also called the contrast, is small. The contrast, C , is defined as the ratio between the planetary and stellar thermal emission, F_p and F_{star} :

$$C = \frac{F_p}{F_{\text{star}}} \left(\frac{R_p}{R_{\text{star}}} \right)^2, \quad (2.10)$$

where R_p is the radius of the planet and R_{star} is the stellar radius. In order to increase the contrast and reveal the planetary signal, high contrast imaging (HCI) methods are used. Firstly observations are optimized by minimizing the blurring effects of the Earth's atmosphere and blocking out the central diffraction Airy disk of the star, this results in an observation similar to the schematic presented in the right panel of Fig. 2.2. Then, post processing is applied to remove the diffraction pattern (Simonnin, 2025).

The intensity of the light emitted by hot stars peaks toward shorter and bluer wavelengths, thus when observed in infra-red the star appears fainter. Therefore, a favorable contrast between the stellar and planetary light is obtained for hot planets on orbits with large orbital separation from a hot star observed in the infra-red (de Pater & Lissauer, 2015). HCI is biased to finding these types of planets. Fig. 1.1 shows an infra-red image of a young (~ 20) Myr system, the β Pic system. The hot ($\sim 8000\text{K}$) A-type star has been masked out, revealing the signal from a giant planet, β Pic b. The system also hosts a second planet, β Pic c. It was originally not detected by direct imaging, as it is on a too close-in orbit and has a lower contrast. It was first detected using the RV method (Lagrange et al., 2019) and only later confirmed using direct imaging (Nowak et al., 2020) as the RV method provided initial clues about the location of the planet. β Pic c was the very first planet discovered using RV and later confirmed by HCI (Zurlo, 2026).

By monitoring the system over time, the direct imaging method provides the period of the planet around its star and the semi-major axis can be estimated from their projected separation. By comparing analyzing the

time-series observation of the movement of the planet in its orbit, orbital parameters could be determined from the motion of the planet. The radius of the exoplanet can also be measured from the light emitted by the planet, using Stefan-Boltzmann's law:

$$F_p = \sigma T_{\text{eff}}^4 \iff L_p = 4\pi R_p^2 \sigma T_{\text{eff}}^4, \quad (2.11)$$

where F_p is the bolometric flux per unit surface [Baudino et al. \(2019\)](#), L_p is the luminosity of the planet, R_p is the planetary radius, σ is the Stefan-Boltzmann constant and T_{eff} is the effective temperature of the planet. L_p can be measured from the direct observation, however the temperature of the planet has to be inferred from the spectrum of the planet. Different species will be present in the atmosphere depending on its temperature ([Nowak et al., 2020](#)), for example the presence of molecules indicates a colder temperature as these get disassociated at high temperatures. Note that this method is model dependent and assumes that the observed planet is a blackbody emitter. Therefore it is more uncertain compared to determining the radius using the transit method, where the radius can be measured directly from the transit depth.

Due to the complexity of this technique, significantly lower number of exoplanets have been detected using HCI than using the RV and transit methods, however the HCI method provides detections that are unachievable by the other methods making every detection very valuable. The HCI method is the only method that is capable of observing planets on wide orbital separations from their host stars. As discussed above the RV and transit methods are biased toward detecting planets that are located close-in to their star. In contrast to the other techniques, HCI targets primarily young planetary systems (< 500 Myr) making it particularly well suited for detecting and studying giant planets which have recently formed or are still undergoing formation ([Zurlo, 2026](#)). The HCI technique is powerful as can be used to gather photometric, spectroscopic and astrometry measurements of the planets detected ([Claudi, 2016](#)).

Even though direct imaging is challenging due to the low contrast between the planetary and stellar light, it opens up an important science task: the characterization of the atmospheres of non-transiting exoplanets. This is possible by spectral analysis of the emission light from exoplanets. Since the direct imaging method does not require a specific orientation of the planet, it makes characterizing its atmosphere possible for a much larger sample of planets than is possible today with transmission spectroscopy ([Claudi, 2016](#)). This method has already been used to characterize the atmospheres of young, giant planets by the James Webb Space Telescope (JWST; e.g., [Miles et al. 2023](#)). In the future, the 39 meter European Extremely Large telescope (ELT) will target Earth-like exoplanets with the aim of determining their atmospheric composition ([Palle et al., 2025](#)).

2.3 Exocomets

Comets and asteroids are small bodies in our solar system that evaporate material when they are close enough to the Sun. They are carriers of knowledge about the formation of the solar system. With the advances in technology, astronomical observations have been able to peek into stellar systems other than our own. Exocomets are comet-like bodies in extrasolar systems. In this context, a comet-like body is a minor body that is sublimating material, not necessarily an icy body. While the term "comet" is well defined in our solar system, a comet is a minor icy body that sublimates material, the term "exocomet" does not specifically refer to an icy body, but rather to all minor bodies sublimating ice or rock ([Iglesias et al., 2025](#)).

Exocomets were first observed in 1987 in the β Pictoris system (β Pic) through spectroscopic absorption of the gas released by comets ([Ferlet et al., 1987](#)). They were later also observed using photometry ([Zieba et al., 2019](#)). Several different systems have been observed to also host exocomets ([Rebollido et al., 2020](#); [Strøm et al., 2020](#); [Iglesias et al., 2025](#)). Below, explained are the observational methods as well as common exocomet characteristics.

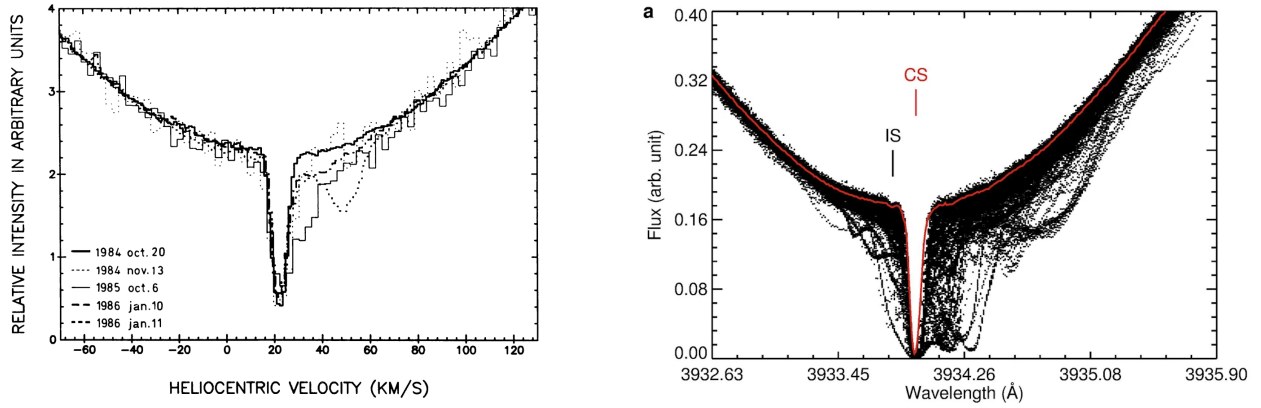


Figure 2.3: Spectroscopic exocomet observations in β Pic in the CaII K line. **Left panel:** The figure shows the very first discovery of exocomets by Ferlet et al. (1987). It shows stable components: a broad photospheric stellar line and a narrow absorption feature from the circumstellar disk together with several time-variable red-shifted absorption components that have been attributed to exocomets. Credit: Ferlet et al., A&A, 185, 267, 1987, reproduced with permission © ESO. **Right panel:** This figure shows the same spectral line is shown but with over one thousand observations spanning over eight years. The figure shows that the exocomet phenomenon is highly time-variable, with over six thousand events found from the spectra presented here. The figure is sourced from Kiefer et al. (2014). Reproduced with permission from Springer Nature.

2.3.1 Spectroscopic Observations

For the first three decades of exocomet observations the leading observational method was spectroscopy. Exocomets are characterized as time-variable, non-periodic absorption features in the spectrum of the host star. When the exocomet is located at a distance close enough to its host star it will sublimate material. This material will form a gas cloud called the coma and later it will form the tails of the comet as the body moves away from the sublimated material (Swamy, 1997). When an exocomet transits in front of its host star, this gaseous cloud will absorb a portion of the stellar light in different wavelengths depending on the composition of the sublimated gas. As exocomets are minor bodies, they will be on a range of different orbits and the absorption will be observable on a stochastic time-scale.

The very first exocomet observation was reported by Ferlet et al. (1987) who saw a variation in the stellar spectrum of β Pic over time, specifically in the CaII K line (393.366 nm ; Edlén & Risberg 1956). They observed β Pic over the course of 2 years with a 2.7 m telescope at the Mc Donald Observatory as well as a 1.4 m telescope at the European Southern Observatory (ESO) in La Silla obtaining spectra of an instrumental resolution equivalent to 3 km/s. Present in all their spectra is a stable, narrow absorption feature at a radial velocity of ~ 0 km/s relative to the star. They report that in addition to this component, they also observe red-shifted absorptions which appear and disappear from the spectra between the different observations, see the left panel of Fig. 2.3. Ferlet et al. (1987) theorize that they could be absorptions of cometary bodies that fall in toward the star. Note that red-shifted absorption variability was detected in lines of iron using the International Ultraviolet Explorer (IUE) by Kondo & Bruhweiler (1985) and Lagrange et al. (1987) however Ferlet et al. (1987) were the first to report spectroscopic variations and link them to exocomets.

Since the first discovery of exocomets in β Pic, thousands of spectra have been obtained of the system. Kiefer et al. (2014) present a survey of 8 years of archival data obtained by the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph (Mayor et al., 2003) on the ESO 3.6 meter telescope in La Silla. In the data consisting of over 1,000 spectra Kiefer et al. (2014) found over 6,000 variable absorption features attributed to exocomets in the CaII K and H lines, see right panel of Fig. 2.3.

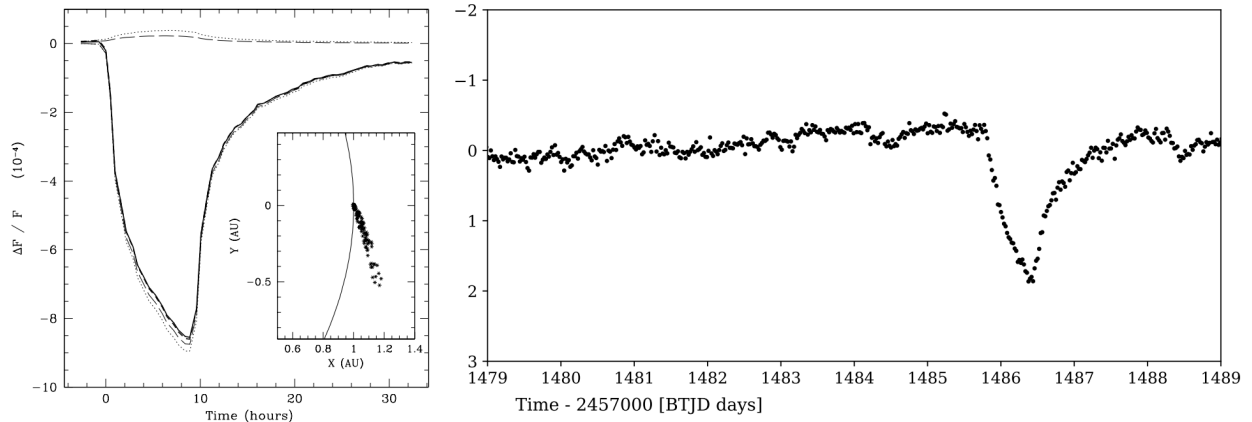


Figure 2.4: **Left panel:** The figure shows a predicted photometric observation, a transit light curve of an exocomet occultation of its host star. Credit: Lecavelier des Etangs et al., A&A, 343, 916, 1999, reproduced with permission © ESO. **Right panel:** A real TESS light curve of an exocometary transit observed in β Pic by Zieba et al. (2019). Credit: Zieba et al., A&A, 625, L13, 2019, reproduced with permission © ESO. Note that there is a large similarity between the prediction by Lecavelier Des Etangs et al. (1999) and the observations by Zieba et al. (2019).

β Pic exocomets have been observed in several different species, among others Na (Hoeijmakers et al., 2025), Fe (Kondo & Bruhweiler, 1985; Lagrange et al., 1987; Vidal-Madjar et al., 2017), Al (Deleuil et al., 1993) and C (Deleuil et al., 1993; Roberge et al., 2000) in addition to the Ca absorptions discussed above. Spectroscopic observations have successfully identified exocomets in other systems than β Pic, among them HD 172555 (see Table 1 in Iglesias et al. (2025) for an overview) and recently in the planet forming system PDS 70 (Novais et al., 2025) through variable absorptions of Na.

2.3.2 Photometric Observations

Even though spectroscopy has been the dominant method of exocomet observation for over 30 years, Lecavelier Des Etangs et al. (1999) predicted that exocomets could also be detected using photometry. They use numerical models of exocomet tails transiting in front of their host stars to predict how such light curves could look like and predict highly asymmetric photometric features, see left panel of Fig. 2.4. The asymmetry arises from the fact that the opacity of the transiting body varies during the course of the transit. As can be seen in the example from Fig. 2.4 the comet nucleus which is fully opaque moves into the line-of-sight first, causing a dip in the ingress of the light curve. It is followed by the less opaque tail causing the asymmetry in the egress of the transit light curve, which is in contrast to the symmetric light-curve observed for exoplanets as discussed in Sect. 2.2.2.

Photometric observations of comets around main sequence stars other than the Sun were first done in 2018 by Rappaport et al. (2018) using data from the Kepler mission. Observations of exocomets were reported in the systems KIC 3542116 and KIC 11084727, and were characterized as observations of likely exocomets due to their asymmetric transit features that match the prediction of Lecavelier Des Etangs et al. (1999). The first photometric observation of an exocomet in the β Pic system was performed using the Transiting Exoplanet Survey Satellite (TESS) by Zieba et al. (2019). One of three transits reported in the study can be seen in the right panel of Fig. 2.4. The light curve shows the asymmetric shape predicted by Lecavelier Des Etangs et al. (1999). This observation was of high scientific value, as it confirmed the spectroscopic exocomet observations in β Pic. With both spectroscopic observations in several elements and photometric observations of exocomets, β Pic became the first system with confirmed exocomets. Today, only one more system shares this title with β Pic, namely HD 172555 (Iglesias et al., 2025). Comet-like objects have also been observed transiting in front of white dwarf stars (Vanderburg et al., 2015).

Table 2.1: A summary of the stellar parameters of β Pic.

Parameter	Value	Reference
Mass (M_{star})	1.77 $M_{\odot}$	Lacour et al. (2021)
Radius (R_{star})	$1.759 \pm 0.241 R_{\odot}$	Di Folco et al. (2004)
Age	23 ± 3 Myr	Mamajek & Bell (2014)
Effective Temperature (T_{eff})	8054 ± 96 K	Baburaj et al. (2026)
Distance to Earth	19.28 ± 0.19 pc	Crifo et al. (1997)
Spectral Type	A6V	Gray et al. (2006)
Rotational Velocity ($v \sin i$)	130 km/s	Royer et al. (2007)
Surface Gravity ($\log g$)	4.18 ± 0.13 [dex](cgs)	Baburaj et al. (2026)
Metallicity [Fe/H]	-0.28 ± 0.14 [dex]	Saffe et al. (2021)
Apparent Magnitude (V_{mag})	3.86	Ducati (2002)

2.4 β Pictoris

The nearby planetary system β Pictoris (β Pic) is located only 19.28 ± 0.19 pc away (Crifo et al., 1997). It has an A6V-type star (Gray et al., 2006) that is hot, 8054 K (Baburaj et al., 2026) bright, $V_{\text{mag}} = 3.86$ (Ducati, 2002) and visible to the naked eye from the southern hemisphere. The star is a fast-rotator with a projected rotational velocity of $v \sin i = 130$ km/s (Royer et al., 2007), has a surface gravity of $\log g = 4.18$ [dex](cgs) (Chilcote et al., 2017; Baburaj et al., 2026) and an estimated metallicity of $[\text{Fe}/\text{H}] = -0.28$ [dex] (Saffe et al., 2021). The stellar parameters of β Pic are summarized in T. 2.1. β Pic hosts two gas giants, β Pic b and c discovered in 2009 (Lagrange et al., 2009; Lagrange et al., 2010) and 2019 (Lagrange et al., 2019) respectively. In addition to the planets, a circumstellar dust disk has been observed in the system through infrared excess (Aumann, 1985). The system is young, estimated to be 23 ± 3 Myr old (Mamajek & Bell, 2014) making it an interesting target for the study of evolution of planetary systems. Importantly, time-variable absorptions have been observed in the system in mainly CaII, but also other species, and were attributed to so-called falling evaporating bodies (FEBs) also referred to as exocomets.

β Pic is the archetype exocomet system as exocomets have been observed here extensively for nearly four decades. With the large amount of observational data owing to the high frequency of the exocomet phenomenon, β Pic is a playground for exocomet science providing a unique opportunity of studying these bodies in a bright, nearby system that is oriented nearly edge-on. Furthermore, β Pic is a system with two confirmed exoplanets (Lagrange et al., 2010; Lagrange et al., 2019) with well constrained masses and orbital parameters (Blunt et al., 2020; Lacour et al., 2021) making it possible to perform informed numerical simulations on the system in order to constrain the dynamical evolution and possible exocomet creation mechanisms.

2.4.1 The Circumstellar Disk

An important part of the β Pic system is the presence of the circumstellar dust disk oriented edge-on to the line of sight from Earth (Smith & Terrile, 1984). The disk was initially discovered with the Infrared Astronomy Satellite (IRAS) through the presence of excess infrared radiation emitted by cold dust orbiting the star (Aumann, 1985). The disk has been observed repeatedly since its discovery and several interesting sub-structures have been unveiled. An inner cavity was observed in the disk (Roques et al., 1994). Its outer edge, also being the inner edge of the planetesimal disk is estimated to be located at ~ 50 AU (Dent et al., 2014; Matrà et al., 2019). At an orbital distance of ~ 80 AU a warp in the brightness distribution of the disk has been observed (Burrows et al., 1995; Mouillet et al., 1997) and it was later confirmed that the warp is a secondary disk which is inclined with respect to the main disk (Heap et al., 2000; Golimowski et al., 2006). Golimowski et al. (2006) observed the β Pic system with the Hubble Space Telescope (HST) Advanced Camera for Surveys and obtained coronagraphic images of the disk, showcasing a main disk oriented nearly edge-on and a secondary disk component, inclined $\sim 5^\circ$ with respect to the primary component. Furthermore, observations show a peak brightness asymmetry between the south-west and north-east sides

of the disk (Dent et al., 2014). The complex structures present in the dust disk point to ongoing dynamical interactions in the system. The complex disk morphology was thought to be evidence for the presence of planets in the system, years before the two known planets were discovered (Heap et al., 2000; Okamoto et al., 2004).

In addition to the complex large-scale morphological structure of the disk, the planetesimals in the disk have been observed to follow an interesting distribution. Matrà et al. (2019) measure vertical distribution of planetesimals in the β Pic dust disk in order to relate the β Pic disk to the Kuiper Belt in our solar system and to potentially draw conclusions about the presence of additional, unseen planets. In order to draw conclusions about the inclination distribution of larger planetesimals in the β Pic disk, Matrà et al. (2019) observe it in 1.3 mm reflected light with the Atacama Large Millimeter Array (ALMA) telescope which provided the resolution necessary to vertically resolve the edge-on oriented disk in this long wavelength. Observing the disk in shorter wavelengths probes smaller grains which are susceptible to inflated inclinations and eccentricities due to excitation by radiation pressure (Thébault, 2009). Matrà et al. (2019) find that, similarly to the Kuiper Belt, the disk of β Pic has a bimodal distribution of planetesimals. They identify two populations of planetesimals in the disk. One population is dynamically cold meaning that the orbits of the planetesimals are not significantly inclined while the planetesimals of the second population are on significantly ($\sim 10\text{-}20^\circ$) inclined orbits and is thus this population is dynamically hot. The presence of an inclined population of planetesimals in the Kuiper belt has been linked to the outward migration of Neptune during the evolution of the solar system (Nesvorný, 2015), therefore Matrà et al. (2019) hypothesize that this finding could indicate the presence of a third, unseen planet in the β Pic system.

2.4.2 Planets

β Pic b was the first planet discovered in the system by Lagrange et al. (2009) and later confirmed by Lagrange et al. (2010) using high-contrast direct-imaging. The observation was possible due to the low infra-red output of the young A-type star, the relatively high infra-red radiation and the large orbital separation of the young and hot β Pic b (Lagrange, 2014). The planet has a semi-major axis of 9.91 AU and a mass of 11.73 M_J (Lacour et al., 2021). The second planet of the system, β Pic c, was discovered almost 10 years later by Lagrange et al. (2019) through radial velocity variations of the star. It was later confirmed by Nowak et al. (2020) using astrometry. β Pic c is located interior to the orbit of β Pic b, inside the habitable zone of the system at a semi-major axis of 2.70 AU and is similar in mass to the outer planet (Lacour et al., 2021). Note that both the planets are eccentric in particular β Pic c which has a significant eccentricity of 0.33 (Lacour et al., 2021). The β Pic system contains at least two planets that are perturbing one another, see Sect. 2.1 for a discussion about planetary perturbation. As a result of the secular perturbation from its planetary colleague/companion, the argument of periapsis of β Pic c *precesses* (changes) over time as has been shown through numerical simulations (Beust et al., 2024). Due to the high eccentricity of the orbit of β Pic c, this precession potentially has a large impact on the system's geometry over time.

A long time before the discovery of the two planets the presence of at least one massive planet in the system was theorized. Firstly, observations of the disk structure gave strong suggestions of the presence of one or more planetary companions to β Pic. The presence of an inner cavity in the disk was thought to be cleared by at least one planet (Roques et al., 1994). A rotationally symmetric warp was observed in the inner disk by Burrows et al. (1995) who argue that this observed warp is only stable on a time-scale corresponding to 1/20th of the age of the system and thus it is likely that at least one inclined, massive planet is present to maintain the observed warp. A transiting body was photometrically observed and theorized to be either a dust cloud or a planet (Lecavelier Des Etangs et al., 1997). Finally, the presence and properties of *Falling Evaporating Bodies* (FEBs) was a strong argument for the presence of at least one eccentric planet in the system (Beust et al., 1990, 1991; Beust & Morbidelli, 1996) and using FEB statistics the presence of at least two planets was predicted (Levison et al., 1994).

Finally, the recent discovery of two populations of planetesimals in the β Pic disk points towards the presence of an additional planet, outside of the orbit of β Pic b. Matrà et al. (2019) argue that the presence of β Pic b

is not enough to explain the dynamically hot family of planetesimals observed in the disk. They compare the β Pic disk to the solar system Kuiper Belt, in which a bimodal distribution of planetesimals has also been discovered and linked to the outward migration of Neptune in the early evolution of the system and discuss that this observational result might point to a third, perhaps outward migrating, planet in β Pic.

Recently the β Pic system has become a target for the search after exomoons, i.e moons orbiting exoplanets. The system with its two directly imaged giant planets is monitored by precise astrometric measurements possible due to close proximity of it to Earth. So far, exomoons have not been successfully detected around the β Pic planets, however [Macias et al. \(2025\)](#) were able to place constraints on how massive hypothetical moons at maximum must be in order to not have been detected with the astrometric monitoring and they find a maximal moon mass of 0.6 R_J. Moons or other circumplanetary material was searched for with photometric observations of the transit of the Hill sphere of β Pic b ([Kenworthy et al., 2021](#)). The planet itself has a small inclination of 88.99° ([Lacour et al., 2021](#)) and does thus not transit however it has a Hill sphere large enough to be transiting. Material trapped in this Hill sphere, such as moons or other material, could then be observable using photometry. So far, this method has not been able to detect any exomoons or other circumplanetary material around β Pic b ([Kenworthy et al., 2021](#)). [Poon et al. \(2024\)](#) argue for the presence of at least one exomoon around β Pic b due to the non-zero obliquity of the planet. The large obliquity can be explained by the presence of a moon inducing secular spin-orbit resonances and thus increasing the obliquity of the planet, as shown by their theoretical predictions and N-body simulations. This is one of the possible mechanisms which are thought to be behind the large obliquities of gas giants in our solar system ([Saillenfest et al., 2021](#)). The theoretical predictions about a presence of an exomoon around β Pic b will have the possibility to become more accurate as the planet's obliquity is measured by the JWST as discussed by [Poon et al. \(2024\)](#).

2.4.3 Falling Evaporating Bodies (FEBs)

After the detection of the β Pic edge-on dust disk ([Aumann, 1985](#); [Smith & Terrile, 1984](#)), spectroscopic observations of the star were performed with the International Ultraviolet Explorer (IUE; [Kondo & Bruhweiler 1985](#); [Lagrange et al. 1987](#)). These observations showed variations in absorption of metal lines. Similar variations were discovered in Ca by [Ferlet et al. \(1987\)](#) who were the first study to link these time-variable red-shifted absorptions to falling evaporating bodies or exocomets (see [Sect. 2.3](#) for a detailed description of exocomet observations). The FEB name was adopted due the vast majority of the early observations of exocomets in β Pic being red-shifted, moving away from the observer and "falling" toward the star. The β Pic system has since been observed extensively and the term FEB has for the most part been replaced by the term *exocomet*. Even though hundreds of exocomets are detected every year in β Pic, their origin and dynamical evolution still remains unconstrained.

One of the largest surveys of exocomets in β Pic was performed by [Kiefer et al. \(2014\)](#) who analyzed several years of HARPS ([Mayor et al., 2003](#)) observations of the system and found over 6,000 spectroscopic features attributed to gaseous clouds produced by the sublimation of exocomets, looking at the CaII K and H lines. Each absorption feature attributed to an exocomet was fitted with a Gaussian profile and the absorption depths, radial velocities relative to the star as well as the full width half maximum (FWHM) of the absorption were measured. They also fit for the ratio between the area of the cloud Σ_c and the area of the stellar disk Σ_{star} , the surface ratio $\alpha = \Sigma_c / \Sigma_{\text{star}}$. [Kiefer et al. \(2014\)](#) also determine the dust production rate and transit-distance of the exocomets by adopting a dynamical model of evaporation. In their study, [Kiefer et al. \(2014\)](#) were able to make statistical inferences and draw conclusions about the exocomet population of β Pic due to the large amount of observational data investigated. Their main conclusion is that there are two distinct populations or families of exocomets in the system, family "S" and family "D". The two families have different sets of physical properties.

The S exocomet family is identified by shallow absorption features which [Kiefer et al. \(2014\)](#) interpret as comets that are depleted in volatiles and thus are old and exhausted. They have small surface ratios α , meaning that the surface area of the cloud is small compared to the stellar disk. Exocomets from family S

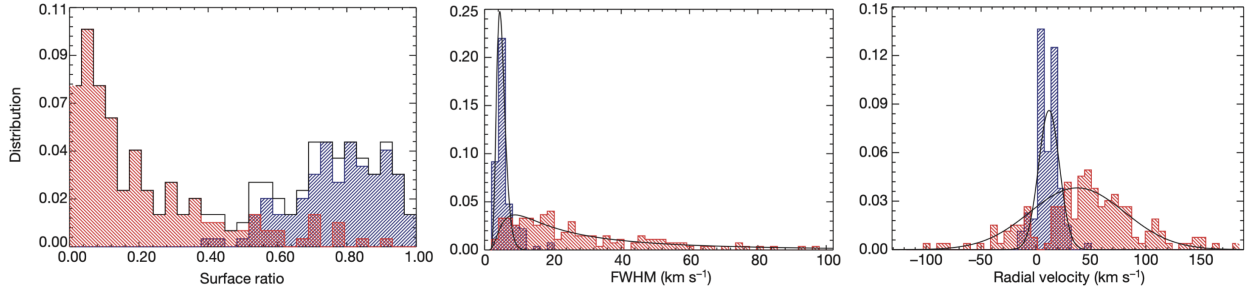


Figure 2.5: Distributions of the physical properties of exocomets observed in β Pic through variable spectroscopic absorptions in CaII over the course of several years, as surveyed by Kiefer et al. (2014). The figure shows evidence for two distinct populations/families of exocomets, family S in red and family D in blue. **Left panel:** The distribution of surface ratios α , so the area of the exocomet cloud compared to the surface area of the stellar disk. **Middle panel:** This panel shows the measured FWHM of the absorptions attributed to exocomets. **Right panel:** The radial velocity distributions of the two exocomet populations. Figure sourced from Kiefer et al. (2014). Reproduced with permission from Springer Nature.

have large FWHM with a broad distribution. Kiefer et al. (2014) explain that the FWHM of the absorption feature is related to the distance between the exocomet and the star. A broad FWHM indicates a short transit distance of exocomets from population S which is also confirmed by the dynamical evaporation model that finds an average transit-distance of $d_S \approx 10 \pm 3 R_{\text{star}}$.

Exocomets from family D are producing deep absorption lines and are therefore interpreted to be rich in volatiles. They have large surface ratios, meaning that the cloud covers most of the stellar disk. They have lower values and more narrow distribution of their FWHM than the S family and thus expected to transit at longer distances further away from the star, the dynamical model finds a transit distance of $d_D \approx 19 \pm 4 R_{\text{star}}$. Note that even this larger distance at transit is still small, meaning that both families of exocomets are observed in the vicinity of the star on distances smaller than 0.2 AU. The dust production rate of population D is higher than population S, indicating more active surfaces. Kiefer et al. (2014) propose that the higher dust production rate could mean that the exocomets from family D either have larger nuclei than family S, or that they have layers of ice exposed by recent fragmentation. The surface ratios and FWHM distributions of the two families are presented in the two left panels of Fig. 2.5.

An important property of the two exocomet populations is their distributions of radial velocities, see the rightmost panel of Fig. 2.5. The S family has a broad distribution of RVs, $v_{r,S} \approx 36 \pm 55$ km/s. The RV distribution is centered at 36 km/s meaning that the majority of population S exocomets are red-shifted, but due to the large width of the RV distribution, a significant portion of the exocomets from population S are blue-shifted. The broad RV distribution indicates that the exocomets of population S are scattered on a variety of orbits. Kiefer et al. (2014) claim that the distribution of orbits of family S exocomets is typical for objects trapped in mean motion resonance with a massive planet. Note that this study was performed before the discovery of β Pic c and thus relies on models which only include one planet.

The exocomets from family D have radial velocities that are more similar to each other with a narrow RV distribution of $v_{r,D} \approx 16 \pm 6$ km/s indicating that the D family exocomets are on neighboring orbits with similar arguments of periapsis relative to the line of sight. Kiefer et al. (2014) theorize that the D family exocomets could be the remains of the fragmentation of one or more parent bodies explaining why their orbits are so similar.

In this thesis, I aim to reproduce two populations of exocomets in β Pic by comparing the RVs of simulated particles with the RV distribution presented by Kiefer et al. (2014). Moreover, the goal of this work is to

propose mechanisms behind the creation of exocomets in β Pic and determine if exocomets from the two populations are created by the same mechanisms or have different dynamical evolutions as well as identifying possible reservoirs of the two exocomet populations.

2.4.4 Possible Exocomet Creation Mechanisms

The RV distributions of the exocomets in β Pic provoke questions about the mechanism or mechanisms behind their creation. One of the most interesting properties of the exocomet population is that most absorptions observed are red-shifted, see left panel of Fig. 2.5. This places a constraint on the mechanism responsible for the creation of these exocomets, it must be asymmetric in nature. As discussed by Beust et al. (2024), the in-transit radial velocity of a body on a highly elongated orbit depends mostly on the periastron distance of the body and, importantly, on the longitude of periastron of the orbit with respect to the LOS. This implies that red-shifted and blue-shifted absorptions correspond to different orbital orientations relative to the LOS. The uneven distribution of exocomet longitudes of periastron indicates that they originate from one side of the disk (Beust et al., 1990) and therefore any mechanism that cannot explain this non-uniformity must be ruled out. An example of such mechanism is the von Zeipel-Lidov-Kozai (ZLK) effect (von Zeipel, 1910; Lidov, 1962; Kozai, 1962) which has been used to explain the creation of sungrazing comets (comets approaching the Sun on distances closer than $3.5 R_{\odot}$) in the solar system (Bailey et al., 1992; Jones et al., 2018). The ZLK effect is rotationally invariant and the created cometary orbits should not have a preferred longitude of periapsis. It is therefore not the leading explanation of how exocomets in β Pic are created, as discussed by Beust et al. (2024).

As discussed by Kiefer et al. (2014), the similar alignment of some of the exocomets observed in β Pic could be explained by the fragmentation of one large parent body. Tidal break-up of a large body was proposed as an explanation to the observed alignment of exocometary bodies by Beust et al. (1996). It is however difficult to explain how the rate of exocomet creation would remain as consistent as it has been observed to be over the last four decades. Another possible mechanism to be responsible for the creation of the exocomets in β Pic are secular resonances. This mechanism was proposed by Levison et al. (1994) who show that the observed RV asymmetry would be a natural consequence of comet creation by secular resonances with planets. The secular resonance would excite the cometary orbits in the same direction, resulting in an alignment of their periastra. The majority of the observed exocometary events would therefore have a similar RV, which would depend on the orientation of the system with respect to the observer. This exocomet creation method would require at least two planets. Levison et al. (1994) performed their study using a model of the solar system, where the v_6 secular resonance is highly effective at exciting the orbits of minor bodies such as comets. Therefore, their results are not necessarily applicable onto other systems such as β Pic. Beust & Morbidelli (1996) argue that the v_6 secular resonance is the result of the very specific alignment of bodies in the solar system and that the probability that β Pic would have this same alignment is low. Other secular resonances are much weaker and could not explain the exocomet phenomenon. Today, two planets are discovered in β Pic and it is known that the dynamical makeup of the two systems are vastly different from each other.

A mechanism which could explain the directionality of the orbits and the continuous creation of the observed β Pic exocomets is mean-motion resonance with a planet. The MMR mechanism is explained in detail in Sect. 2.1. It has been proposed as the mechanism of β Pic exocomet creation even before the discovery of the system's planets due to the asymmetric distribution of radial velocities of the observed exocomets (Beust & Morbidelli, 1996; Th  bault & Beust, 2001). These studies showed that if the system hosts a planet that is eccentric ($e \geq 0.05$) it will have the ability to increase eccentricities of planetesimals enough for them to become exocomets. According to theoretical studies, the planet should also be located at a semi-major axis of ~ 10 AU (Beust & Morbidelli, 2000). Beust & Morbidelli (1996) argue that MMR is the preferred mechanism for the creation of the exocomet phenomenon in β Pic and that it is more likely than any of the other mechanisms discussed above as it can explain the preferred directionality of the exocometary orbits and sustain exocomet production over decades. Kiefer et al. (2014) find for family S exocomets would have a periastron longitudes distributed roughly between 0° and 50° , which align with the model of Beust & Morbidelli (1996) for a population of exocomets created via a 4:1 resonance with a planet located at an

orbital distance of $a = 4.5$ AU. Note that such a planet could realistically not exist in the β Pic system, as the region between the two already discovered planets, located at 2.70 AU and 9.91 AU respectively, has been shown to be dynamically unstable on short time-scales (Rodet & Lai, 2024; Beust et al., 2024). Therefore, population S exocomets are not necessarily created through MMR as claimed by Kiefer et al. (2014). Beust et al. (2024) draws the parallel between β Pic and the solar system as the Kirkwood gaps in the solar system asteroid belt are thought to have been created through MMR with Jupiter and therefore β Pic could be seen as a representation of an early solar system.

2.4.5 Transit Distances of Exocomets

The origins of the exocomets of β Pic are still unknown. It is unclear whether the comet-like bodies are sourced from reservoirs in the close vicinity of the star, as proposed by Beust et al. (2024) and are thus primordially devolatilized or if they originate from the outer system and could possibly have retained volatile content until the moment they are observed transiting the star. Gaining a better understanding of the origins of the exocomets of β Pic could help relate them to the comets/asteroids in our own solar system. If exocomets are sourced from reservoirs in the outer system, they could possibly enrich β Pic c and other potential planets in the habitable zone of β Pic with volatiles such as water. Comets and early inward scattering of planetesimals are two mechanisms that are thought to be responsible for the delivery of water to Earth from the outskirts of the Solar system (O’Brien et al., 2018). It is challenging to constrain the origin of the exocomets from observational data, however it is possible to estimate the distance of the cloud released by the comet-like body at the time of observation, the transit distance.

Kiefer et al. (2014) determine the transit distances of exocomets in their survey by making use of the fact that physical properties of the exocomets in β Pic such as their transit distance or the dust production rate in their comae, can be derived from measuring quantities of the CaII cloud transiting in front of the star. Kiefer et al. (2014) compute the evaporation efficiency for each detected exocomet. The evaporation efficiency is a quantity that describes how efficiently the exocomet nucleus transforms the stellar flux into evaporation of gas and dust. In this model, Kiefer et al. (2014) assume that the nucleus of exocomets are covered in ice and that the radiation from the star is used to heat up and sublimate the ice into water vapor. Any energy left over from doing that is either absorbed by the crust of the exocometary nucleus or re-emitted by its surface. This left-over radiation will thermalize the sublimated gas which heats up, its velocity increases and it escapes from the nucleus while picking up dust grains from the mantle, dragging them along. The gas transfers kinetic energy to the dust grains which gain velocity. The evaporation efficiency depends on the properties of the nucleus of the exocomet such as size, albedo and fragmentation. Since the evaporation efficiency depends on the stellar flux, it also depends on the distance from the star.

The evaporation efficiency can be measured from an absorption spectrum by using the fact that total amount of momentum gained by CaII atoms in the cloud is equal to the momentum of the photons absorbed by the same CaII atoms, so momentum is conserved in the exocomet gas cloud. Using momentum conservation, the evaporation efficiency is determined by the surface ratio α and the absorption depth A of the spectral exocomet feature. Using this method, Kiefer et al. (2014) find that there is a large difference between the two exocomet families in terms of evaporation efficiency. Exocomets from family D are evaporating almost ten times as efficiently as the exocomets of family S meaning that if the comets were located at the same distance from the star, comets from population D would produce almost ten times more dust.

Aside from the evaporation efficiency and dust production rate, Kiefer et al. (2014) also estimate transit distances of the exocomets using a hydrodynamical model developed by Beust & Tagger (1993) in which the observed ions are dragged out from the nucleus by the evaporating water gas, but are slowed down at large distances from the nucleus due to radiation pressure which then accelerates them in the anti-stellar direction, creating a shock surface. Using this model, Kiefer et al. (2014) relate the measured surface ratios α and the evaporation efficiency η to the distance between the cloud and the star, and thus extracting the transit distances of the exocometary material. They find that exocomets from family D transit at distances further away from the star than comets from population S, but in general Kiefer et al. (2014) find that all exocomets

in their sample transit on distances shorter than 0.2 AU from the star.

The transit distances of family S exocomets in β Pic were also determined by Kennedy (2018) who measured the acceleration of exocomet absorption and was able to fit orbital parameters to the acceleration, finding that all exocometary features investigated had a transit distance shorter than 0.2 AU, which is in agreement with the results of Kiefer et al. (2014). The topic of transit distance of exocometary clouds in β Pic was also recently revisited by Vrignaud & Lecavelier des Etangs (2024) and Vrignaud & Lecavelier des Etangs (2026) who use a new method of determining the transit distance. Vrignaud & Lecavelier des Etangs (2024) showed that in β Pic exocomet tails the excitation state of FeII is predominantly set by the amount of stellar flux the ions are exposed to and thus by how far away from the star they are located. After applying their method on a single exocomet from family S, they find a transit distance of 0.4 AU which is slightly further away from the star than what was found by both Kiefer et al. (2014) and Kennedy (2018). In a follow up, Vrignaud & Lecavelier des Etangs (2026) use the same method to find the distances to three family D exocomets and find significantly larger distances than ever reported before: 0.88, 4.7 and 1.52 AU. Distances to exocomets from family D were only also found by Kiefer et al. (2014) who find much shorter transit distances. Vrignaud & Lecavelier des Etangs (2026) argue that the hydrodynamical model presented by Beust & Tagger (1993) and used by Kiefer et al. (2014) to determine the distances is based on the unrealistic assumption that the ions sublimated from the nucleus evolve dynamically by collisions with neutral hydrogen gas. The exocomet tails are thought to be ionized (Vrignaud et al., 2024, 2025), which changes the dynamical evolution of the ions in the tail.

The model of Beust & Tagger (1993) make several assumptions. First of all, they assume that the ions form a stationary flow around the nucleus of the comet. They argue that even if the radiation pressure could vary during the orbit of a comet, they provide an estimate that this change would be negligible. Secondly, they also assume that the flow is symmetric around the comet-to-star axis which is only valid for gas close to the nucleus as the tail is subject to curvature effects at a larger distance from the nucleus. However this assumption holds since it is gas from the close proximity of the nucleus which is responsible for the variable absorption features attributed to exocomets, Beust & Tagger (1993) argue. Furthermore, Beust & Tagger (1993) also assume that the ions modeled collide with a neutral surrounding medium. This is inaccurate, as the tails of exocomets are thought to be ionised (Vrignaud et al., 2024, 2025) and therefore the Coulomb interaction between ions would be of importance to include in the model.

In summary, by determining the transit distances of material released by exocomets it is thought that exocomets from family S transit at distances shorter than 0.5 AU from the star (Kennedy, 2018). This could mean that the exocomets from this family either migrated from the outer system and are observed when they already have migrated into the vicinity of the star, or that they originate from a reservoir in the proximity of the star. Interestingly, when exocomets from family D were investigated by Vrignaud & Lecavelier des Etangs (2026), the transit distances found were much larger than expected, up to almost 5 AU from the star meaning that the observed exocomets must originate from a region further away from the star than the observed transit distance, likely from beyond the water ice line of the system located at approximately 8 AU (Lodders, 2003). However, Vrignaud & Lecavelier des Etangs (2026) argue that the cometary dust observed by them must have sublimated in the vicinity of the star where temperatures are high enough to sublimate significant amounts of the refractory material they observe. This material in gas form must then have over time migrated to the large distances reported. It is still unclear what mechanism could explain such a migration of material and why it would happen for family D exocomets and not family S. The discovery of large transit distances of exocometary material opens up for an interesting discussion about the origins of exocomets, suggesting that the close-in reservoir proposed by Beust et al. (2024) might not be the only probable region of exocomet sourcing.

In this thesis I aim to contribute to the discussion about possible exocomet origins by performing N-body simulations of the system to try and pinpoint regions of the β Pic system that are dynamically stable on a time-scale which corresponds to the age of the system and thus regions where rings of planetesimals could reside. Furthermore, I aim to investigate if there reservoirs do produce exocomets at a time-scale corresponding to the age of the system to be able to predict potential exocomet sources and potentially exclude the possibility

of volatile content in β Pic exocomets.

2.5 Modeling Sublimation

The variable spectroscopic features observed in β Pic and attributed to exocomets are produced due to stellar light being absorbed by gas released from the exocometary nucleus when it transits in front of the star. In order to relate theoretical studies to actual observations it is therefore important to understand the dynamics of the gas released by the exocomets. β Pic exocomets have displayed differences in properties depending on what element is observed. Only years after the first exocomet detection in β Pic, [Beust et al. \(1989\)](#) noticed differences in the observed radial velocities of different elements. Absorptions in MgII and AlIII are observed at red-shifts of ~ 330 - 460 km/s, while the absorptions in CaII are observed in smaller red-shifts of ~ 40 - 50 km/s. Note that the numbers presented in [Beust et al. \(1989\)](#) are based on only two years of exocomet observations, [Kiefer et al. \(2014\)](#) presented a more recent survey of a large amount of observations and found that the CaII absorptions have RVs between ~ -100 - 150 km/s. While this range is significantly broader than the one presented by [Beust et al. \(1989\)](#), their idea still stands. MgII and AlIII absorptions have a larger red-shift than CaII and this is interpreted as them having a higher in-fall velocity toward the star by [Beust et al. \(1989\)](#).

[Hoeijmakers et al. \(2025\)](#) make the first discovery of NaI in β Pic exocomets and find that exocometary sodium absorption is rare compared to CaII and is only observable for exocomets which produce particularly strong CaII absorption. Due to the low ionization energy of NaI, [Hoeijmakers et al. \(2025\)](#) expect it to not be observable far away from the cometary surface, as it would have become ionized by then in contrast to CaII which is harder to ionize and thus expected to have a longer lifetime, possibly explaining why CaII is visible in exocomets more often than NaI. NaI is observed in exocomets that exhibit particularly high CaII outgassing which could provide a shield from ionizing photons protecting the NaI ions from quick ionization.

Differences in observed radial velocities of absorption from different elements as well as rare observation of certain elements could depend on differences in the radiation pressure exerted on the different elements. Species strongly affected by radiation pressure could be pushed radially away from the star which would result in different observed radial velocities and could also make species affected particularly strongly invisible to observations, as they are blown out of the narrow transit window as well as gaining high RV, moving away from the wavelength range where the feature is expected, possibly blending with other spectral features.

2.5.1 β -factors

One important property of the sublimated exocometary gas is the fraction between the radiation pressure acceleration, g_{rad} , and the gravitational acceleration, g_{grav} acting on the particles in the gas, the so-called β -factor. The gravitational acceleration at a distance r from the star can be estimated using:

$$g_{\text{grav}} = \frac{GM_{\text{star}}}{r^2}, \quad (2.12)$$

and the radiation pressure induced acceleration on a gas is defined as:

$$g_{\text{rad}} = \frac{1}{c} \int \kappa_{\nu} F_{\nu} d\nu, \quad (2.13)$$

where κ_{ν} is the mass absorption coefficient of the gas and F_{ν} is the stellar spectral flux density which varies as a function of distance from the star ([Rybicki & Lightman, 1986](#)). Thus, the β -factor can be described as:

$$\beta \equiv \frac{g_{\text{rad}}}{g_{\text{grav}}} = \frac{\frac{1}{c} \int \kappa_{\nu} F_{\nu} d\nu}{\frac{GM_{\text{star}}}{r^2}}. \quad (2.14)$$

Note that in cases when the flux is modeled from the emergent specific intensity, it is convenient to evaluate g_{rad} and g_{grav} at the stellar surface, $r = R_{\text{star}}$. If $\beta < 1$, then the radiation pressure acting on the gas is

smaller than the gravitational acceleration. A particle with mass m bound in an orbit around a star of mass M at a semi-major axis a will have the binding energy $E_{\text{bind}} = -GMm/(2a)$. The radiation will contribute with energy as it irradiates the particle at distance r , $E_{\text{rad}} = \beta GMm/r$. Assuming a circular orbit ($r = a$), the particle will remain bound in the Keplerian orbit around the star if $\beta < 0.5$, the particle will feel a reduced dynamical mass of $(1 - \beta)M$, where M is the mass of the star. If $\beta > 0.5$, then the particle is no longer bound by the gravitational motion (Fernández et al., 2006). When $\beta > 1$ the acceleration induced by the radiation pressure is stronger than the gravity and the particle is effectively blown away moving radially to larger distances away from the star. Note that β is independent on the distance from the star, as both the radiation pressure and gravity scale as r^{-2} . The radiation pressure and gravitational accelerations can thus be estimated at any distance, for example the stellar surface. Comparing the β -factor for different elements could explain differences in observed properties of exocomets.

In order to investigate why different species are observed to have different RVs in transit, Beust et al. (1989) develop a numerical model for simulating the different species. The model includes forcing from gravity, radiation pressure and collisions between the ions in the gas. They evaluate the contribution from the radiation pressure by calculating the β - factor for CaII, AlII and MgII. They find the force on a gas induced by radiation f_{rad} using the following:

$$f_{\text{rad}} = \sum_{\text{all transitions}} \frac{\pi e^2}{m_e c^2} f F_{\nu}, \quad (2.15)$$

where F_{ν} is the stellar spectral flux density, f is the oscillator strength of the transition, e is the elementary charge and m_e is the mass of the electron. Note that Beust et al. (1989) use only two transitions per species to find the radiation pressure induced force. The stellar flux used by Beust et al. (1989) is the result of an interpolation between the measured flux of two stars of the types A1V and A7V for the optical range and using a flux from a spectrophotometric library (Jamar et al., 1976) for the ultraviolet wavelength range. They find that the radiation pressure on all the ions investigated is significantly larger than the gravity and that the radiation pressure is higher for Ca II than it is for Mg II and Al III explaining why the latter two are moving toward the star much faster, as Ca II is being slowed down and pushed away by radiation pressure. The model developed by Beust et al. (1989) was used in later studies by Beust et al. (1990) and Beust et al. (1991) who use it to successfully reproduce spectral absorption features that match real observations of exocomets in β Pic.

The β -factors for several different ionic species in β Pic were calculated by Fernández et al. (2006) who use the following formula for calculating the force on the gas induced by radiation pressure:

$$f_{\text{rad}} = \frac{1}{c} \sum_{j < k} F_{\lambda} \sigma_{jk} = \frac{1}{8\pi c^2} \sum_{j < k} \frac{g_k}{g_j} A_{kj} \lambda_{jk}^4 F_{\lambda}. \quad (2.16)$$

where F_{λ} is the stellar spectral flux density which is dependent on distance and σ_{jk} is the cross section for the transition from level j to level k . Note that σ_{jk} is integrated over wavelength. Above, g_k and g_j are the statistical weights of levels k and j , A_{kj} is the Einstein coefficient for spontaneous emission from level k to level j and λ_{jk} is the wavelength of the level transition. In their calculations, they assume that the gas they are interested in is located at a few AU from the star where the temperature is low enough such that collisions and radiative excitations of the gas are less efficient than radiative de-excitations and thus the gas particles can be assumed to be in the ground state. This approach has also recently been used by Lehtmetts et al. (2026). The differences between the studies of Fernández et al. (2006) and Lehtmetts et al. (2026) is that they use a different model for the emergent stellar flux. Fernández et al. (2006) use a PHOENIX model spectrum (Hauschildt et al., 1999) with a $T_{\text{eff}} = 8000$, and $\log g = 4.2$. They then broaden the spectrum to model the fast-rotating β Pic using a linear limb-darkening law with $\epsilon = 0.5$. Lehtmetts et al. (2026) use model spectra from ATLAS9 which are of low resolution and therefore less affected by broadening caused the high rotation speed of the star, therefore Lehtmetts et al. (2026) do not apply any line-broadening.

2.5.2 Photoionization and Velocity Boost

An atom consists of a nucleus surrounded by shells of electrons at different potential energies. When a photon is absorbed by an atom, it gains the energy of the photon. The energy gained by the atom can then excite an electron from its ground state to a higher energy level. Photoionization happens when a photon excites an atom to the degree an electron is liberated from it, the electron becomes unbound. This happens if the energy of the photon ($h\nu$) absorbed by the atom is larger than the binding energy of the electron, so if $E_{\text{binding}} \leq h\nu$, where h is Planck's constant and ν is the frequency of the photon. A more energetic photon, with a higher frequency, will be able to ionize electrons with higher binding energies. The energy levels of the atom are called ionization edges, photons that have lower energies than the ionization edge of a certain level won't be able to liberate electrons from that level. After photoionization, the atom is a positively charged ion (Longair, 1992).

Photons with energy higher than the ionization edge of a electron energy level will have a non-zero probability of ejecting the electron and ionizing the atom. This probability is called the *photoionization cross-section*. It decreases with photon frequency, roughly by ν^{-3} . For a specific element, the ionization cross-section will vary over frequency (energy), not only decreasing for larger frequencies but also featuring sharp increases in cross-section at specific frequencies. These cut-off frequencies correspond to the energy of different levels inside the atom. Depending on different elements and the structure of the electron energy levels/shells within them, the photoionization cross-section will vary with frequency in a different way.

The photoionization time-scale t_{ion} is a measure of how long it takes on average for an atom to become ionized in a radiation field. It can be found from the photoionization rate Γ of an ion, given by:

$$\Gamma = \int_{\nu_0}^{\infty} \left(\frac{4\pi}{h\nu} \right) \sigma_{\nu} J_{\nu} d\nu, \quad (2.17)$$

where ν_0 is the ionization frequency threshold of the atom investigated, h is the Planck constant, σ_{ν} the photoionization cross-section and J_{ν} is the mean intensity (Rutten, 2003; Osterbrock & Ferland, 2006; Hillier, 2023). If the radiation is isotropic and follows Planck's law for blackbody radiation, the mean intensity equals the intensity emitted such that $J_{\nu} = I_{\nu}$ (Hillier, 2023). Note also that per definition $F_{\nu} = 4\pi I_{\nu}$ (Rybicki & Lightman, 1986).

Fernández et al. (2006) find photoionization rates for 19 different neutral atomic species in the β Pic debris disk evaluated at a distance of 100 AU from the star. They apply the assumption that all electrons are in their ground states. Then, Eq. (2.17) becomes:

$$\Gamma = \int_0^{\infty} \frac{F_{\nu}}{h\nu} \sigma_{\nu} d\nu, \quad (2.18)$$

where F_{ν} is the flux received by the atom. Note that the lower bound of the integral is different in the two formulas. It does not affect the calculation, as the cross-section is zero below the ionization threshold ν_0 . Thus, integrating over frequencies lower than ν_0 will not change the calculation, as there is no cross-section in that region of the frequency axis. The photoionization time-scale can be computed as the inverse of Γ , $t_{\text{ion}} = 1/\Gamma$.

An atom will receive a velocity boost from the radiation pressure it experiences. This velocity boost depends on both the β -factor and the photoionization rate:

$$v_{\text{ion}} \simeq \beta \frac{GM}{r^2} \frac{1}{\Gamma}, \quad (2.19)$$

where G is the gravitational constant, M is the mass of the star and r is the distance between the atom and the star. The larger the β -factor, the more efficiently will the atom be boosted away from the star. However, at the same time if Γ is large, the atom will ionize quickly and experience a smaller boost. Note that since Γ depends on F_{ν} it also depends on the distance to the star and is proportional to r^{-2} , the velocity boost v_{ion}

is constant with distance r (Fernández et al., 2006).

The aim of this study is to calculate the β - factors for elements observed in outgassed exocometary material in β Pic in order to relate to the finding of previous studies on this topic as well as to gain an understanding for why certain elements are more commonly observed in β Pic exocomets than others, such as the recently discovered Na (Hoeijmakers et al., 2025). This work is also an attempt at improving the models of previous works by also including higher ionization states in the analysis instead of solely focusing on the ground state as had been done before. The objective of this thesis is to also calculate the ionization rates, velocity boosts and ionization time-scales for the elements observed in β Pic exocomets. Using these calculations this work aspires to comment on the observability of elements, primarily NaI, in the exocometary clouds.

Chapter 3

Methodology

In this chapter the methods used to model the dynamical evolution of the β Pic system and its exocomets are described. In [Sect. 3.1](#) the N-body code as well as the integrator used for the purpose of this project are introduced and explained. This choice is also motivated and put in a historical context. The simulation set-up and initial conditions are presented in [Sect. 3.2](#). [Sect. 3.3](#) and [Sect. 3.4](#) describe how the simulation results were analyzed in order to draw meaningful comparisons with exocomet observations in β Pic and conclusions about exocomet composition respectively. The sensitivity of the simulation results to the adopted initial conditions is tested in [Sect. 3.5](#). Finally, [Sect. 3.6](#) presents the methodology used for constructing a dynamical model of the sublimated exocometary material.

3.1 N-body Simulations

As reviewed in [Sect. 2.1](#), the motion of two bodies in a system is well defined by elliptic orbits. The position of the bodies can thus be analytically predicted for a point in time. This breaks for a system of three massive bodies, where no such analytical solution can be found and this is called the *three-body problem* (or N-body problem for N amount of bodies). The N-body problem can be solved using numerical simulations which find accurate numerical solutions to the equations of motion. To evaluate the evolution of the β Pic system which contains a primary star and two planets, a clear three-body system, a numerical simulation must be performed.

Note this means that N-body simulations provide approximations to the solution of the equations of motion. The accuracy of this solution depends on the precision of the simulation. Usually this means that there is a tradeoff between accuracy and computational resources, as a more accurate solutions will typically be computationally more expensive.

3.1.1 REBOUND

The N-body simulations were performed using the REBOUND open-source and multi-purpose N-body code ([Rein & Liu, 2012](#)) designed for applications in astrophysics. As an N-body code REBOUND simulates the gravitationally induced motion of particles allowing for customization such that a wide range of astrophysical problems can be investigated. The code has several different modules for detecting and resolving collisions and a wide range of integrators.

The code initially featured only symplectic N-body integrators ([Rein & Liu, 2012](#)). The main advantages of symplectic integrators are that they have a small energy error accumulation over long time-scales and the major speed increase compared to non-symplectic N-body integrators ([Chambers, 1999](#)). Since symplectic integrators are less computationally expensive than non-symplectic integrators, they can be used to simulate a larger number of particles increasing the statistical power of the simulation while conserving integration time. A challenge with using symplectic integrators is that they use a fixed time-step for the duration of the

simulation. This becomes especially challenging when simulating objects that move on different time-scales such as particles undergoing close encounters. In order to resolve the close encounter a fine time-step is needed and the full simulation must be performed with a higher time-step resolution which might not be necessary for the majority of the simulation. Symplectic integrators are thus a good choice for increasing computational efficiency for simulations of systems of particles which are not undergoing close encounters or have small pericenters.

In this work, close encounters between test particles could not be ruled out and thus the N-body simulations were carried out using the non-symplectic IAS15 (Integrator with Adaptive Step-size control, 15th order) integrator (Rein & Spiegel, 2015). Even though IAS15 is a non-symplectic integrator, it has been found to minimize energy error better than symplectic integrators. Each computer performs calculations to a certain number of decimals and stores quantities in floating-point variables, meaning that errors are unavoidable. If the total energy error is dominated by unbiased float-point round-off errors and truncation errors are negligible, the resulting energy error will only depend on the rounding of the quantities. The energy error will then behave like a random walk and is proportional to the number of integration steps performed n , as $\propto \sqrt{n}$. This is called the Brouwer’s law (Brouwer, 1937; Rein & Spiegel, 2015). The energy error of IAS15 follows Brouwer’s law and behaves like a random walk. Rein & Spiegel (2015) argue that IAS15 is superior to the symplectic integrators it has been compared to in both speed and accuracy. The IAS15 integrator was chosen to simulate the dynamical evolution of planetesimals in β Pic as it has been successfully used to simulate close encounters with cometary particles, debris disks and particles on highly eccentric orbits (Rein & Spiegel, 2015).

The IAS15 integrator approximates the acceleration as a high-order polynomial and uses it to integrate and obtain velocities and positions:

$$\ddot{y}(h) \approx \ddot{y}_0 + b_0 h + b_1 h^2 + \dots + b_6 h^7, \quad (3.1)$$

where $\ddot{y}_0$ is the initial acceleration at the beginning of the time-step such that $\ddot{y}_0 = \ddot{y}(0)$, for the very first time-step this will be the acceleration computed from the initial conditions. Above, $h \equiv t/dt$ is a dimensionless variable which parametrizes the sub-steps that make up one time-step dt . In total, eight sub-steps are performed inside each time-step, including one at the beginning of the time-step. Above, b_k are the polynomial coefficients. The polynomial can be integrated to obtain analytical solutions for the positions and velocities, which will also be high-order polynomial approximations which will depend on the same polynomial coefficients b_k .

In order to get the positions and velocities at the sub-steps, the unknown polynomial coefficients b_k have to be constrained. The coefficients b_k are determined using a predictor-corrector scheme. First, initial estimates for the positions and velocities at the sub-steps (h) are obtained by assuming $b_k = 0$, corresponding to motion with constant acceleration, this is the predictor step. Using these predicted positions and velocities, the accelerations at the sub-steps are evaluated by calculating the acceleration from Newton’s equation of gravity Eq. (2.1). The accelerations computed are then used to find improved estimates of the coefficients b_k such that the polynomial approximation of the acceleration matches the acceleration values calculated at the sub-steps h using Eq. (2.1). The goal is to make sure that the polynomial acceleration approximation matches with the equation of motion evaluated at points within the time-step. The coefficients are in turn used to estimate updated positions and velocities, this is the corrector step. The predictor-corrector steps are repeated until the b_k constants converge and final values for the positions and velocities are found and the time-step ends. The final b_k constants are used as initial estimates for the new time-step. Usually, the predictor-corrector loop needs on the order of two iterations to reach convergence. However, if after 12 iterations the predictor-corrector loop fails to converge, the process is stopped and the step size dt is lowered. This is how IAS15 controls the step-size by implementing an adaptive step-size.

3.1.2 N-body Simulations of β Pic Exocomets

The theoretical explanations of the exocomet phenomenon in β Pic were formulated before the discovery of the systems planets. When a planet was finally detected in the system, β Pic b (Lagrange et al., 2009;

Lagrange et al., 2010) with an eccentricity of 0.1 and semi-major axis of nearly 10 AU (Lacour et al., 2021; Blunt et al., 2020) it seemed to match the predictions made by the theoretical studies (Beust et al., 1990, 1996; Beust & Morbidelli, 1996, 2000). However, the system is more complicated than previously estimated. The discovery of a second, giant planet β Pic c (Lagrange et al., 2019) challenged the theoretical models proposed before. Its location inside the orbit of β Pic b and high mass could potentially disrupt the MMR theory, as discussed by Beust et al. (2024). Even though the MMR mechanism has been tested and shown to still produce exocomets even when adding an interior planet to the system, this was done for a Earth-like planet and not a planet as massive as β Pic c (Beust & Morbidelli, 2000). As the β Pic system is more complicated than estimated by previous theoretical studies due to the discovery of more than one giant planet in the system, recently N-body simulations have been performed to re-investigate the issue. This was done recently by Rodet & Lai (2024) and then later by Beust et al. (2024).

Rodet & Lai (2024) use N-body simulations to investigate the planet-driven scattering of planetesimals and their subsequent migration toward the vicinity of the star. They investigate different planetary properties in order to determine the likelihood and time-scale of the production of stargazers. For this purpose, they simulate a uniform disk of planetesimals in a planetary system in REBOUND (Rein & Liu, 2012) using the IAS15 non-symplectic integrator (Rein & Spiegel, 2015). They investigate two general cases, one case where the planetary system consists only of a star and one planet and a second case with two planets. They find that for a system of a star and one planet the production of stargazing planetesimals is more likely if the planet is more eccentric. To simulate the second case of a star with two planets, Rodet & Lai (2024) use the β Pic system as a model. They initiate the star and planets using parameters found by Lacour et al. (2021), see T. 3.1, together with a disk of 1000 test-particles with uniform distributions of semi-major axis (1-30 AU), eccentricities (0-0.05), inclinations (0° - 2°) as well as arguments of periastron, longitudes of ascending node, and mean anomalies (0° - 360°). They simulate the system for 10 Myr.

From the simulations, Rodet & Lai (2024) conclude that the addition of a second planet significantly destabilizes the system, increasing the probability of the production of stargazing planetesimals from 3% if only β Pic b was included in the simulation, to 30% with both planets included. They find that the inclusion of β Pic c creates a non-negligible likelihood that test-particles initiated on almost all orbital distances become stargazing. The results of the simulation performed by Rodet & Lai (2024) show that there is no significant region that is dynamically stable on a time-scale of 10 Myr, which could be a potential reservoir of exocomets, between 1 and ~ 25 AU. Note that dynamically stable regions that have a narrow spatial distribution could have been missed by Rodet & Lai (2024) due to the low number of test-particles included in their simulation.

A similar simulation of planetesimals in β Pic was performed by Beust et al. (2024) who use the same orbital solution by Lacour et al. (2021) and very similar initial conditions of the simulated test-particle disk as Rodet & Lai (2024), with the exception of a broader semi-major axis range of 0.5 - 45 AU. Beust et al. (2024) use a less computationally expensive symplectic integrator and are able to simulate the star and planets together with a disk of 400 000 test-particles. After simulating for 10 Myr, Beust et al. (2024) are able to identify dynamically stable regions where a non-negligible number of test-particles was able survive the simulation without being ejected. They see stability in a region that has the orbital distance of below 1 AU, as well as several regions between 20-25 AU. They also find that test-particles survive the simulation if they are further than ~ 28 AU, where the planetary perturbations are not strong enough to affect them after 10 Myr. Beust et al. (2024) argues that the regions of stability further away from the star are not potential exocomet reservoirs, as they are on orbits with too large periastron distances to reach the vicinity of the star. The region within 1 AU from the star is presented as a likely exocomet reservoir, where the orbits of planetesimals are excited through MMR with β Pic c and exocomets are generated this way. Beust et al. (2024) also investigates what transit radial velocities the exocomets produced from the region would have and find a good alignment with the results of Kiefer et al. (2014), which are presented in Sect. 2.4. Beust et al. (2024) seems to reproduce the radial velocity of family D exocomets in particular.

In this thesis I aim to relate to the findings of Rodet & Lai (2024) and Beust et al. (2024) by constructing an N-body simulation based on initial conditions inspired by the two simulations. I intent to combine the use

Table 3.1: Stellar and planetary parameters of the β Pic system, reproduced from [Beust et al. \(2024\)](#). Presented here are two solutions, found by [Lacour et al. \(2021\)](#) and following the conventions by [Blunt et al. \(2020\)](#). As the two solutions have been found to produce similar results for N-body simulation studies ([Beust et al., 2024](#)), only parameters from solution 1 were used as initial conditions for the simulations in this thesis.

Object	Parameter	Solution 1	Solution 2
β Pic	$M_{\text{star}} (M_{\odot})$	1.77	1.85
β Pic c	$M_c (M_{\text{Jup}})$	8.41	8.85
	a_c (AU)	2.70	2.60
	e_c	0.33	0.33
	i_c (deg)	88.95	88.82
	Ω_c (deg)	31.05	31.06
	ω_c (deg)	67.70	61.02
	τ_c	0.73	0.71
β Pic b	$M_b (M_{\text{Jup}})$	11.73	10.00
	a_b (AU)	9.91	9.95
	e_b	0.10	0.10
	i_b (deg)	88.99	88.98
	Ω_b (deg)	31.81	31.81
	ω_b (deg)	196.10	202.05
	τ_b	0.71	0.73

of a non-symplectic integrator as implemented by [Rodet & Lai \(2024\)](#) with the large amount of simulated test-particles as done by [Beust et al. \(2024\)](#). The non-symplectic integrator makes it possible to resolve close encounters that I hypothesize are important in creation of exocomets while the large amount of test particles enables resolving patterns in the test-particle distributions and gives a larger statistical power to the study.

3.2 Simulation set-up

In order to investigate the dynamical evolution of exocomets in the β Pic system, an N-body simulation containing the star and the two planets of the system, was initiated in REBOUND. The values for the stellar and planetary parameters used can be found in Table T. 3.1 under solution 1. They were measured and reported by [Lacour et al. \(2021\)](#). Note that in the simulation the orbital plane has an inclination of 0° in contrast to the convention used by [Lacour et al. \(2021\)](#) where an inclination of 90° is defined to be fully edge-on. Thus, the reported inclinations of the planets are $i_c = 88.95^\circ$ and $i_b = 88.99^\circ$ and translating them to the convention used by the REBOUND simulation, given that the orbital planes of the planets share a similar line of nodes, the inclinations are $i_c = 90^\circ - 88.95^\circ = 1.05^\circ$ and $i_b = 90^\circ - 88.99^\circ = 1.01^\circ$. Additionally to the parameters presented in T. 3.1, the star and planets also had defined radii of $R_{\text{star}} = 1.8 R_{\odot}$ for the star which has a measured radius of $1.759 \pm 0.241 R_{\odot}$ ([Di Folco et al., 2004](#)) and $R_c = R_b = 1.4 R_{\text{J}}$ for the planets. The value was chosen from the reported value of the radius of β Pic b of $1.40 \pm 0.04 R_{\text{J}}$ ([GRAVITY Collaboration et al., 2020](#); [Chilcote et al., 2017](#); [Worthen et al., 2024](#)) and the radius of β Pic c was chosen to be equal for the sake of simplicity as the planets are thought to be similarly sized with a radius of β Pic c of $1.2 \pm 0.1 R_{\text{J}}$ ([Nowak et al., 2020](#)).

The system was also simulated with a disk of 133 500 mass-less test-particles, modeling a primordial planetesimal disk of β Pic. The test-particles were initiated with a range of initial conditions: their semi-major axes were uniformly sampled between 0.5 and 45 AU, their eccentricities uniformly sampled between 0 and 0.05 and inclinations also following a uniform sampling between 0 and 2 degrees. Their arguments of periastron, longitudes of ascending node and mean longitudes were all randomly and uniformly drawn from between 0 and 360 degrees. A summary of the initial conditions of the test-particles modeling the primordial planetesimal disk can be found in Table T. 3.2 .

Table 3.2: Initial conditions of the 133 500 simulated test-particles, inspired by Rodet & Lai (2024) and Beust et al. (2024). All parameters constituting the initial conditions follow uniform distributions.

Parameter	Distribution	Unit
a	$\mathcal{U}(0.5, 45)$	AU
e	$\mathcal{U}(0, 0.05)$	
i	$\mathcal{U}(0, 2)$	° (deg)
ω	$\mathcal{U}(0, 360)$	° (deg)
Ω	$\mathcal{U}(0, 360)$	° (deg)
l	$\mathcal{U}(0, 360)$	° (deg)

The initial conditions for the stellar and planetary parameters as well as the initial conditions for the test-particles simulated were chosen to match simulations previously performed by Rodet & Lai (2024) and Beust et al. (2024) as this work aims to relate to their findings. There are however a few differences between the set-ups. First of all, in this work the test-particles are initiated between 0.5 and 45 AU, aligning well with Beust et al. (2024). Rodet & Lai (2024) however simulated the system with a smaller disk of test-particles extending between 1 and 30 AU. Another major difference between the simulation set-ups is the amount of test-particles used. Rodet & Lai (2024) use 1000 particles in their study, while Beust et al. (2024) uses 400 000. This work models the planetesimal disk with 133 500 test-particles, obtaining a similar scale to Beust et al. (2024) while using a more computationally demanding integrator. While the number 133 500 might seem arbitrary, it is grounded in the way the simulation was designed. In order to keep the uniform semi-major axis distribution, 3000 test particles were initiated for each one AU of orbital separation. Since the simulation is for a total of 44.5 AU (between 0.5 and 45 AU) the total number of simulated particles becomes 133 500.

A larger number of test-particles allows for a more robust statistical analysis of the outcomes. Beust et al. (2024) could include a large number of test-particles and provide a statistically robust result due to using a symplectic N-body simulator. While having its perks, such as low computational cost and thus the ability of simulating large amounts of particles, symplectic integrators do not resolve close encounters well and therefore are not well suited for simulations of phenomena which require close encounters. Rodet & Lai (2024) performed a simulation of the β Pic system using a non-symplectic integrator, IAS15 in REBOUND. Being more computationally expensive, a smaller amount of test-particles was used in the study by Rodet & Lai (2024). In the work presented in this thesis, the same non-symplectic integrator as first used by Rodet & Lai (2024) was used simulating a number of test-particles that is on the scale of what was achieved by Beust et al. (2024) in order to combine the ability to accurately resolve close encounters together with a higher resolution allowing for more meaningful statistics.

3.2.1 Classification of Test-Particle Fates

The simulation was set-up as described in Sect. 3.2 and the system was simulated for 25 Myr, a time-scale similar to the estimated age of the system (23 ± 3 Myr ; Mamajek & Bell 2014). During this simulation, the test-particles were tracked and could either survive the whole simulation i.e remain *stable*, or be removed from the simulation. A test-particle could be removed from the simulation if it was classified as *ejected*, *collided* or *stargazing*.

A particle was classified as *ejected* from the system and removed from the simulation if it had a location that was at a distance greater than 150 AU from the star and simultaneously was on an orbit with eccentricity $e > 1$. A test-particle that has an eccentricity larger than one is on an unbound orbit and will leave the system. The reason why the eccentricity is only checked for test-particles with distances greater than 150 AU from the star is to make sure that the particle is actually ejected from the system and not undergoing a close encounter with a planet. Such a close encounter could momentary alter the orbit of the test-particle

and it could be falsely classified as ejected. The 150 AU distance criterion ensures that the particle is well outside of the sphere of influence of the system's two planets, minimizing the risk of false-positive ejection classification.

The test-particles were classified as *collided* if their position overlapped with the position of any of the two planets. Note that test-particles were assumed to be point-like objects and thus did not have a physical radius to them. The planets however had defined radii as described in Sect. 3.2. So, a collision was detected if the position of the point-like test-particle was ever detected inside the radius of β Pic c or b. Instead of evaluating collisions at the end of each time-step, the REBOUND collision routine "line" was used. It assumes that the simulated particles travel on straight lines in-between the time-steps and a collision is flagged if the interpolated positions of test-particles ever cross within the radii of the planets. Using the "line" routine allows for a smaller number of missed collisions, note however that collisions still can be missed as the linear interpolation of position between two time-steps is not always a good approximation, especially in highly dynamically heated regions where close encounters are common, such as in the inner system (≤ 3 AU) of β Pic.

Finally, the test-particles could also be removed and classified as *stargrazing* if they were found on orbits that had a periastron distance that was smaller than 0.4 AU, which is the orbital distance at which calcium is evaporated significantly enough to be observable, this limit was found by Beust et al. (1998). A test-particle was thus labeled as a stargrazer when it became an observable exocomet. In order to ensure that the particle is actually in the vicinity of the star and does not get classified as a stargrazer due to a momentary change of its orbit due to a close encounter, an additional distance criterion was established. Only test-particles with a position smaller than 1 AU from the star and thus not in a close encounter with any of the planets, were classified as stargrazers.

3.2.2 Parallelization of the Simulation

In order to reduce computation time and allow for the simulation of a larger amount of test-particles, the simulation was split up onto several CPU cores that could run simultaneously, parallel to each other. This was possible due to the fact that the test-particles were mass-less and did not interact with each other so in theory, the simulation result would be the same if a test-particle was simulated alone and if it was simulated together with other test-particles. In practice, this is not always the case and should be approached with caution, see Sect. 3.2.3 for an in-depth explanation. For the purpose of this, Joblib (Joblib Development Team, 2024) was used. Because of the adaptive time-step of IAS15 it was favorable to split the simulation into many smaller parts as it is enough for just one test-particle to undergo a close encounter to slow down the simulation for all particles.

In order to minimize the computation time, test-particles initiated close to each other were simulated together. As already discussed, the adaptive time-step of IAS15 slows down the simulation for all particles if just one is experiencing a close encounter. Close encounters are more likely in regions that are dynamically hot. The inner region of the β Pic system is more dynamically hot than the outer regions, as the planets gravitational influence is smaller further away from their orbits. Test-particles initiated at a distance of 1 AU from each other were simulated together, such that the simulations of particles in the dynamically colder regions could finish faster as they were not likely to experience close encounters.

While IAS15 is an integrator which implements an adaptive step-size, this choice depends on several different things, among them the time of integration. If the same system of particles is simulated for 25 million years, IAS15 will choose step-sizes that are on average longer than if the same system is simulated for 25 years. Therefore, in order to control the average resolution of the step-sizes, the simulation was performed in steps. Instead of simulating for 25 million years in one go, the system was simulated in a loop over smaller time-increments. The size of these time-increments therefore dictated the maximal step-size used by IAS15, and limited the average step-size it would choose.

Additionally, the simulation was also split up into two regimes, a low-resolution regime where particles were

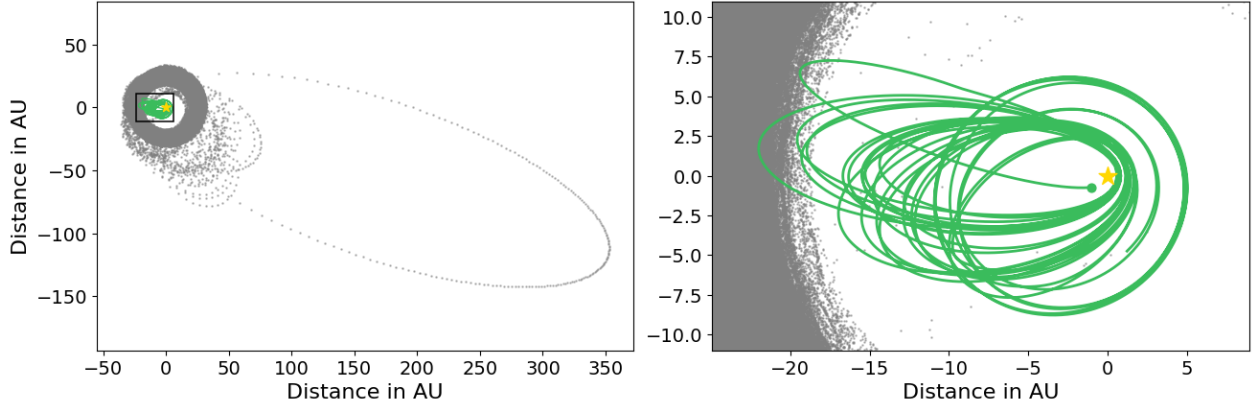


Figure 3.1: Trajectory of one of the 133,500 simulated test-particles. This test-particle was initiated with $a = 25.73$. It was firstly simulated with the low time-step resolution and the trajectory of this part of the simulation is shown with the gray dotted line. After migrating to the inner region, the resolution was increased. The evolution of the same test-particle, simulated with high-resolution is shown in green. The green dot marks the last point before the particle was removed, at this point it had reached an orbit with a periastron distance smaller than 0.4 AU and became classified as a stargrazer.

simulated using a maximal time step of 5 year^{-1} and another high-resolution regime where particles were simulated with a maximal time step of 20 year^{-1} . Particles on orbits that have a periastron smaller larger than 3 AU are simulated using the high time-step resolution. This is because the probability of experiencing close encounters is higher in the vicinity of the star where β Pic c is located. Particles on orbits with periastron distances larger than 3 AU were simulated low time-step resolution in order to increase integration speed. Note that due to the adaptive time-step of IAS15 a close encounter could be accurately resolved even in the low-resolution regime, however as close-encounters are likely to happen more often in the vicinity of the star, the largest time-step the integrator was allowed to take was decreased in order to minimize the risk of error. The maximal time-step limits were chosen based on sensitivity tests performed. Due to the way the simulation was parallelized, particles in the same bin, so particles in the same simulation, had the same initial simulation resolution. Particles initiated on an orbital distance within 3 AU were simulated with the high-resolution while particles initiated further out were initially simulated with the low-resolution. If a particle was to migrate from the outer part of the system to an orbit with a periastron distance within 3 AU, it was removed from its low-resolution simulation and later resumed in a high-resolution simulation.

Fig. 3.1 shows the evolution of the position of one test-particle simulated. This particle was initiated in the outer parts of the system at $a = 25.73$ AU meaning that it is initially simulated using the low-resolution, this part of the trajectory is shown with gray dots. This particular test-particle ended up on an orbit which had a periastron distance smaller than 3 AU while the position of the particle was closer than 5 AU from the star and thus fulfilling the conditions to increase the resolution of the simulation. The green trajectory shows the evolution of the test-particle when simulated with higher time-step resolution. This test-particle was categorized as a stargrazer when reaching an orbit with periastron distance smaller than 0.4 AU, this point is marked with a green dot in Fig. 3.1. Note that the switch between low- and high-resolution is only possible one way. Once a particle crosses the periastron distance boundary, it will never be simulated using the low-resolution again. In order to exclude particles that only briefly are on orbits satisfying the periastron distance criterion, for example when undergoing a close encounter with β Pic b, an additional criterion was imposed on the switch between low- and high-resolution. Test-particles had to additionally be at a distance closer than 5 AU from the star, to make sure that they were not actively undergoing close interactions with β Pic b.

3.2.3 Test-Particles affecting the Timestep

In the simulation, test-particles were mass-less and thus did not have an effect on the overall outcome of the simulation. However, since IAS15 used adaptive time-stepping, test-particles could affect the time-step used by the simulation and thus affect certain aspects of the simulation, such as the trajectories of the test-particles in the simulation and also small changes to the positions of the massive particles (the star and planets). Simulating the star and the planets for 25 Myr alone is therefore not equivalent to running the simulation with additionally N number of test-particles that model planetesimals. Two simulations ran on two different computing cores would be comparable in the statistics of their outcomes, but they could *not* be compared in detail, as the positions of the planets would change slightly from core to core because of the variable time-step of IAS15.

Let us consider an example. On one computing core, N random particles were simulated. The distribution of their initial orbital elements resulted in particles that approach the planets/star frequently, changing the step size of the simulation. In a second core, N particles with other, random orbits were simulated. The particles in this core did not approach the star/planets as frequently and the simulation could thus proceed with a larger time-step size. The size of the time-step affects the positions of the particles, meaning that the two cores of this example could not be compared in that regard. In order to for example find the relative orientation of a test-particle's orbit compared to the orbit of β Pic c, this comparison must be performed on particles ran on the same core. Effectively this means that the positions of the planets and star must be saved from each individual core, if they are of interest. Note however that the two cores in this example could still be compared in terms of statistics of the outcomes of the simulations.

3.3 Extracting Radial Velocities from Transits

In order to relate the simulation to observations of exocomets, a set of stargrazers was chosen to model the exocomets observed today. These will be referred to as *late stargrazers*, test-particles which were classified as stargrazing after 10 Myr of the simulation. These test-particles reach orbits with a periastron distance smaller than 0.4 AU, so become observable as exocomets, at times that correspond to the age of the system on an order of magnitude scale and thus were used to model the exocomets observed in β Pic during the last 40 years.

One of the main conclusions from decades of exocomet observations is the existence of two, distinct families of exocomets with different properties, such as different distributions of radial velocities (Kiefer et al., 2014). Radial velocities of the late stargrazers were extracted in order to relate the theoretical exocomets modeled by the simulation, late stargrazers, to the observed exocomets. To do that a line of sight (LOS) was defined using the convention from Green (1985) also used by Lacour et al. (2021) that provided the parameter solution used for initiating the simulation. Fig. 3.2 which was inspired by Fig. 127 from Green (1985), shows a schematic describing the definition of the orbital alignment. A sphere centered at the primary star "S" is drawn. The direction of the LOS is indicated with the dashed line, crossing the sphere at point "E". The orbit of the secondary companion is drawn in red and the orbital plane of this orbit is marked out by the "HLG" plane. The periastron of the secondary's orbit is marked with "P". As can be seen in Fig. 3.2, by definition the periastron is shifted by $+90^\circ$ from the LOS. Following Green (1985), the LOS was placed at the negative y -axis and the argument of periastron of the orbits investigated was set to $\omega + 90^\circ$ when investigating the properties of late stargrazers crossing the LOS. As an example of using this conversion, the argument of periastron of β Pic c was:

$$\omega_{c,\text{Green}} = \omega_c + 90^\circ = 67.70^\circ + 90^\circ = 157.7^\circ, \quad (3.2)$$

relative to the LOS placed at $-y$. Above ω_c refers to the value of the argument of periastron of β Pic c as reported by Lacour et al. (2021), see T. 3.1. With the LOS defined, the RVs of the late stargrazers could be extracted as they crossed the LOS.

However, this task was complicated by the fact that β Pic c's orbit is precessing. Over time, the orientation of the planet's orbit changes. The argument of periastron ω_c rotates with a period of $\sim 10,000$ years (Beust

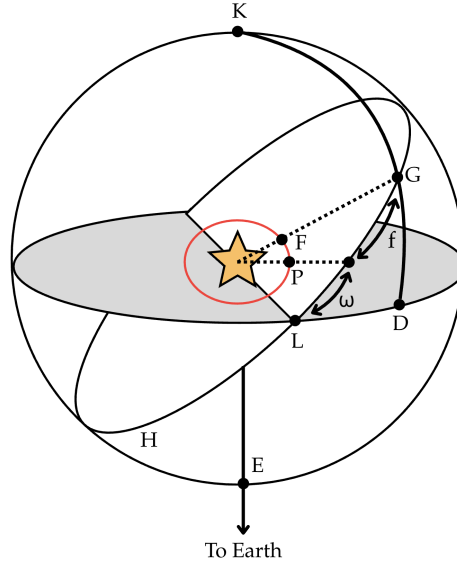


Figure 3.2: A schematic of the definition of orbital parameters, inspired by Fig. 127 from [Green \(1985\)](#) and following the conventions from therein. A sphere is drawn, centered at the primary star, with the points "K" and "E" marking its poles. The direction of the line of sight (LOS) is marked with a dashed line, "E" is the point where the LOS crosses the sphere. The plane "HLG" represents the orbital plane of the companion, the true orbit is drawn in red where the periastron of this orbit is marked with "P" and the current position of the planet is marked with "F".

[et al., 2024](#)). In order to be able to relate to the observations of exocomets in β Pic, the properties of late stargazers should be evaluated at the current orbital alignment of β Pic c. In their study, [Beust et al. \(2024\)](#) chose only test-particles that are stargazing when β Pic c's argument of periastron corresponds to today's value, so about every 10,000 years. This is possible while retaining meaningful statistics due to the ability of including a large amount of test-particles in the simulation because of the use of a symplectic integrator. In the simulation performed for this thesis, a computationally expensive non-symplectic integrator was used, limiting the amount of test-particles simulated. Therefore instead of only using late stargazers which happen to stargaze at the right time, the LOS was de-rotated for all late stargazers, such that the system was viewed in the same alignment as it is observed today. For this purpose the angle $\Delta\omega = \omega - \omega_c$ was defined. It is the difference between the argument of periastron of the late stargazer's orbit ω and the argument of periastron of β Pic c, ω_c , evaluated at the time that the particle is identified as a stargazer.

3.4 Estimating Volatile Contents

One of the most interesting questions still remaining about the exocomets of β Pic is their composition. They have mostly been observed through variable absorption of refractories such as calcium, iron and sodium (see [Sect. 2.3](#)) whereas observations have not detected any outgassed volatiles such as water, OH and CN ([Kenworthy et al., 2025](#)) present in solar system comets. The composition of the comets is debated due to the lack of volatile observations: are the exocomets of β Pic devolatilized and more analogous to the solar system's asteroids, or is it just an observational bias, the opacity of the Earth's atmosphere which has so far been hindering the detection of volatiles in β Pic exocomets?

Observations have so far not been able to confidently conclude whether the exocomets of β Pic are devolatilized or not, however simulations could provide a prediction for this. This is what was done for the purpose of this study by analyzing the results of the global simulation of β Pic and a model disk of planetesimals (see [Sect. 3.2](#)) and using *late stargazers* to model the exocomets observed in β Pic today (see [Sect.](#)

3.3) by tracking their positional evolution to see how long they spend below the water ice-line of the system.

Firstly, the orbital distance of the water ice-line of the β Pic system was calculated using the equation for equilibrium temperature:

$$T_{\text{eq}} = T_{\text{star}} (1 - A)^{1/4} \sqrt{\frac{R_{\text{star}}}{2r}}, \quad (3.3)$$

where $T_{\text{star}} = 8052$ K, $R_{\text{star}} = 1.8 R_{\odot}$ and A the albedo, here assumed to be zero for planetesimals as they have no atmospheres (Quirrenbach, 2022). The distance to the star r where the equilibrium temperature is equal to the condensation temperature of water, 182 K as reported by Lodders (2003), was found to be at an orbital distance of 8.2 AU. Then, the orbits of the late stargrazers were analyzed counting how long they spend within this orbital distance, that is how many years their position in x , y and z coordinates is smaller than 8.2 AU from the star. Note that the time was only counted when $r < 8.2$ AU, if a late stargrazer were to migrate outside of the 8.2 AU boundary again, the time it spent there would not be counted. This time was then compared to the time-scales for which water ice is estimated to be able to survive in bodies modeling the exocomets of β Pic as computed by Karmann et al. (2001).

3.5 Sensitivity Tests

The simulation set-up was based on assumptions about the properties of the system, which were used as initial conditions. Several of the system parameters used are estimations with a certain amount of uncertainty associated with them. The radii of the planets are highly uncertain, as they are inferred from the light emitted by the planet, using Eq. (2.11). This method requires the assumption of a planetary temperature which is in turn inferred from the spectrum of the planet and is therefore highly model dependent and uncertain. Normally, a more precise and accurate radius measurement can be made through transit photometry, by measuring the depth of the transit light curve created by the transiting planet. In the case of the planets of β Pic this is impossible, as they are non-transiting planets. As the measurements of the planetary radii are uncertain, the sensitivity of the simulation to changing these was tested. If substantially changing the planetary radii would not affect the results significantly, they could be considered robust against differences in planetary radii. If not, the results would be dependent on the choice of planetary radii and sensitive to this uncertain property and therefore could only be applicable to a system where the planets have the chosen radii. The radii of the β Pic planets might differ from this choice, and therefore the simulation results would not necessarily be applicable to β Pic. A sensitivity test was performed to see how the size of the radii of the planets affected the branching ratios and the production of late stargrazers from the selected region. To test this, a smaller simulation including test-particles seeded between 23 and 24 AU was run with the same parameters as described in Sect. 3.2 for the global simulation, with the exception of the planetary radii which were doubled.

In order to resolve the orbital evolution of test-particles and at the same time minimize computational time, a sensitivity test of different maximal time-steps was performed. This was done by running simulations of the system with a small number of test-particles initiated at different orbital distances and varying the maximal time-step. The maximal time-step was decreased and the orbits of the particles studied. With every decrease the orbit of the same test-particle would change significantly, until a point was reached when each subsequent decrease would result in a similar orbital evolution, leading to the same classification of the test-particle. This point was reached at 5 years^{-1} for particles evolving outside of the orbit of β Pic c (~ 3 AU) and 20 years^{-1} for particles located interior to this limit. As described in Sect. 3.2.2, a particle initiated outside of the orbit of β Pic c would initially be simulated using the low-resolution maximal time-step, but if it ever crossed this boundary it would be simulated using the high-resolution time-step, see also Fig. 3.1. So, one test-particle could be simulated using two different time-steps. The sensitivity of the simulation results to the choice of maximal time-step and the switching of resolution when simulating a fraction of the test-particles was tested by selecting a small batch of test-particles, initiated between 23 and 24 AU. This batch of test-particles was simulated using the exact same set of initial conditions as described in Sect. 3.2, but this time all particles were simulated using the high-resolution time-step at all times.

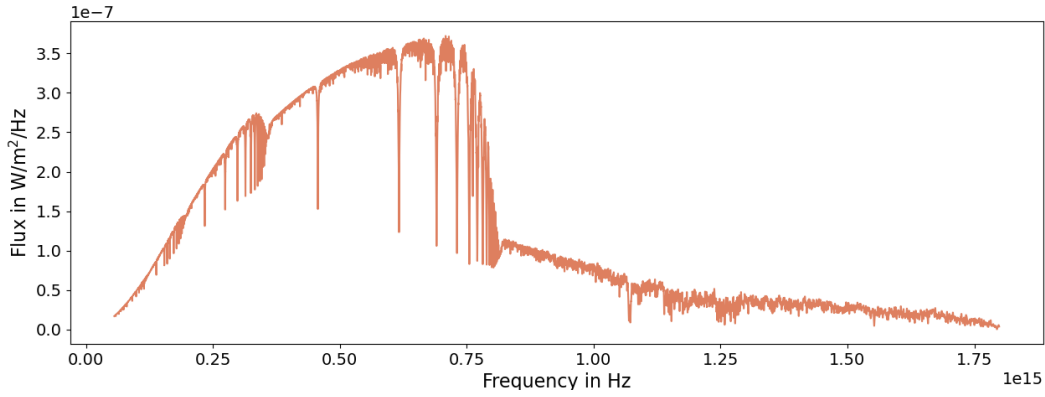


Figure 3.3: A model spectrum of β Pic. It was obtained from the PHOENIX Göttingen Spectral Library (Husser et al., 2013) using the parameters: $T_{\text{eff}} = 8000$ K, $\log g = 4.0$ and $[\text{Fe}/\text{H}] = 0.0$. The spectrum was broadened using the StarRotator code (Hoeijmakers et al., 2024).

3.6 Modeling Sublimated Exocometary Material

In order to understand the observations of exocomets in β Pic, the properties of the gas released by the exocomets was studied in addition to the dynamical modeling described in the previous sections. To form an understanding about the dynamics of the outgassed particles, the ratio of between the acceleration induced by radiation pressure and gravity, the β -factor, was computed for species detected in β Pic exocomets and compared to previous literature. The methodology explaining this calculation is described in Sect. 3.6.1. Additionally, the ionization time-scale was calculated for the same elements, this methodology is explained in Sect. 3.6.2.

For the purpose of calculating both the β -factors and the ionization rates for elements in the β Pic environment a model of the flux emitted by a β Pic like star was produced. See Eq. (2.14) and Eq. (2.18) respectively, both equations are including the F_{ν} term. The stellar flux was obtained by producing a model spectrum of a β Pic-like star. This was done using the StarRotator code (Hoeijmakers et al., 2024) which uses model high resolution photosphere spectra from the PHOENIX Göttingen Spectral Library (Husser et al., 2013) and simulates the broadening of spectral lines due to stellar rotation. The model spectrum used was for a star of $T_{\text{eff}} = 8000$ K, $\log g = 4.0$ and $[\text{Fe}/\text{H}] = 0.0$, in order to model β Pic as well as possible with a non-continuous parameter grid, see Sect. 2.4 for the measured stellar parameters. Fig. 3.3 shows the model spectrum used for the calculations in this work.

Since β Pic is a fast rotator with a rotational velocity of ~ 130 km/s (Royer et al., 2007), the spectrum is significantly affected by rotational blurring, the spectral lines are significantly Doppler-broadened. The Doppler-broadening can result in blending of spectral lines, as deep lines get significantly broadened and their width spans over the same wavelength range as other lines. Additionally to the broadening, StarRotator also models limb-darkening. As the planets of β Pic are non-transiting, the limb darkening parameters have not been measured for the star. Therefore, an approximation was made and the limb-darkening parameters of a similar star were used. WASP-189 (HR 5599) is a fast rotating A-type star with an effective temperature of $T_{\text{eff}} = 8000 \pm 100$ K (Anderson et al., 2018) and thus it is a star similar to β Pic. A transiting ultra-hot Jupiter was found around WASP-189 by Anderson et al. (2018) and the quadratic limb darkening parameters were later measured by Lendl et al. (2020) to be $u_+ = u_1 + u_2 = 0.550^{+0.016}_{-0.017}$ and $u_- = u_1 - u_2 = 0.440^{+0.066}_{-0.065}$. These limb-darkening parameters were used to broaden the PHOENIX model spectrum. StarRotator uses a quadratic model for the limb-darkening following, de Mooij et al. (2017) the law is presented in Eq. (2.7). From the u_+ and u_- values from Lendl et al. (2020), the following quadratic limb-darkening parameters were calculated and used: $u_1 = 0.495$, $u_2 = 0.055$.

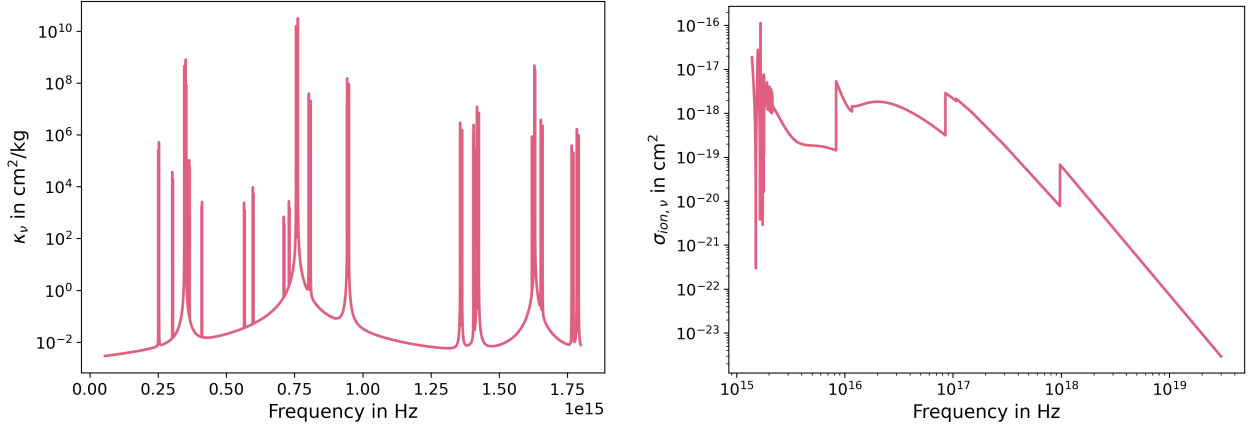


Figure 3.4: **Left panel:** The opacity model for CaII, from DACE (Data & Analysis Center for Exoplanets (DACE), 2025). **Right panel:** The photoionization cross-section for CaII from PhiDRATES (Huebner & Carpenter, 1979; Huebner et al., 1992; Huebner & Mukherjee, 2015).

3.6.1 Calculating the β -factors

With the aim to gain an understanding for the properties of the outgassed material of β Pic exocomets, the ratio between the radiation pressure and gravitational acceleration acting on a species in the gas, the β -factor, was computed and related to literature values provided by Beust et al. (1989), Fernández et al. (2006) and Lehtmetts et al. (2026). As can be seen from Eq. (2.14), the β - factor is a ratio between the radiation pressure induced acceleration and the gravitational acceleration acting on a particle. The gravitational acceleration was computed using Eq. (2.12) and the stellar parameters presented in Sect. 2.4. The radiation pressure induced acceleration for each species investigated was computed using Eq. (2.13), which uses the mass absorption coefficient κ_ν and the stellar flux F_ν .

The mass absorption coefficient, or opacity coefficient as it is also called was obtained from the DACE opacity database (Data & Analysis Center for Exoplanets (DACE), 2025) for each investigated species. The opacity model selected is at a pressure of 1.00×10^{-8} Bar, corresponding to a very low pressure as is expected from inter-planetary medium. The opacity model used is also valid for a temperature of 6100 K, which is the highest temperature possible to obtain from DACE. Vignaud & Lecavelier des Etangs (2024) investigated absorption from a particular exocomet which transited in front of the star at a close distance of ~ 0.43 AU. Looking at 96 different spectral lines of Fe II, they derived an excitation level diagram for the element, it can be seen in the left panel of Fig. 3.5. They found that the gas appears to be populated at an excitation temperature of $T_{\text{ex}} = 8190 \pm 160$ K, a temperature close to the effective temperature of the star which is evidence that the gas is located in a radiative regime, which means that the excitation structure of the gas particles is dictated by the amount of stellar flux received and the excitation energy is equal to the effective temperature of the star, such that $T_{\text{ex}} = T_{\text{eff}} \approx 8000$ K. The radiative regime appears when the electron density is low and when the gas is located close to the star, Vignaud & Lecavelier des Etangs (2024) put this distance limit at ~ 0.5 AU. Gas released from exocomets transiting further away from the star follows a more complex energy distribution.

Finally, as both the flux and mass absorption was modeled, the two models were transformed onto a common frequency axis and multiplied with each other before the resulting curve was integrated over, following Eq. (2.12). The flux model was initially on a wavelength axis, and it was transformed to frequency using $F_\nu = F_\lambda \frac{\lambda^2}{c}$. The opacity model was initially on a wavenumber grid and was transformed to frequency using $\kappa_\nu = \frac{\kappa_{\tilde{\nu}}}{c}$. The resulting flux model can be found in Fig. 3.3 and the opacity model for CaII can be found

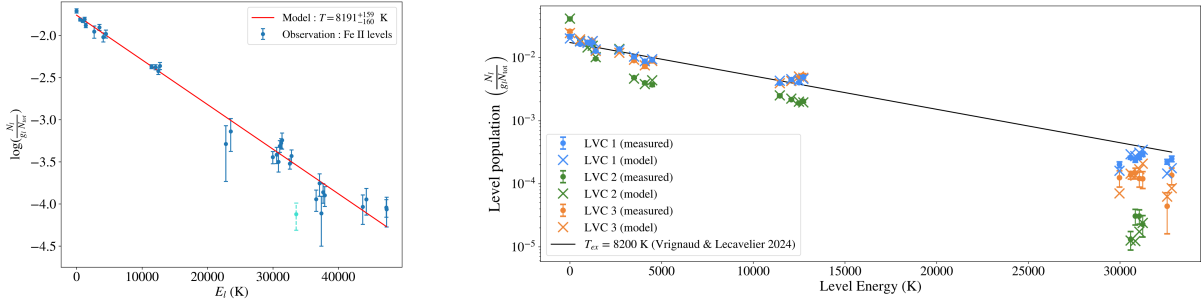


Figure 3.5: **Left panel:** The figure shows the excitation diagram of Fe II for the close approach transiting comet, as investigated by Vrignaud & Lecavelier des Etangs (2024) from whom this figure is sourced. 96 different Fe II lines with different level energies were analyzed and the excitation population follows a model where the excitation temperature is similar to the effective temperature of the star, $T_{\text{ex}} \approx T_{\text{eff}} \approx 8000$ K. This is indicative of a radiative regime. Credit: Vrignaud & Lecavelier des Etangs (2024) licensed under CC-BY 4.0. **Right panel:** The population levels of the excitation states of three different exocometary gas clouds/tails plotted against the energy of the level. The same radiative regime model is indicated with a black line. Credit: Vrignaud & Lecavelier des Etangs (2026) licensed under CC-BY 4.0.

in the left panel of Fig. 3.4. The opacity model included more data-points than the flux model, it was resolved to a higher degree, the opacity data from DACE contained around 3.75 times as many data-points as the StarRotator generated PHOENIX spectrum. Therefore, the flux model was interpolated onto the frequency grid of the opacity model, and the two were multiplied with each other. After multiplying these models with each other, an integration under the resulting curve was performed using a trapezoidal integration method. This method is an approximate solution to an integral which works by dividing the full range of the integral into smaller ranges Δx . The integral is estimated by calculating the area of trapezoids of the width Δx (Süli & Mayers, 2003). The accuracy of the method is increased as Δx becomes smaller and the integral is approximated using a higher number of trapezoids. A higher number is required for functions of sharp gradient changes.

In order to test if the trapezoid method of integration resolved the sharp peaks resulting from the opacity function, the profile of the peak was studied. It can be found in Fig. 3.6, where the $\kappa_\nu F_\nu$ peak around the Ca II K line is shown to be very well resolved with hundreds of data points making up the peak. This means that the trapezoid integration function will have no trouble accurately integrating under the curve, as the Δx is small, and thus that it will not underestimate the area. This method was therefore chosen to perform the integration and determine the radiation pressure induced acceleration.

The modeling done here assumes that the gas from exocomets is in the radiative regime and that the excitation level populations are dictated by the stellar flux, such that the excitation temperature is equal to the effective temperature of the star, which is around 8000 K. This assumption is made even though the simulation results (see Results, Fig. 4.6) show that exocomets are expected to be transiting the LOS at a wide range of distances, even larger than 1.5 AU, meaning that a significant portion of the observed absorbing exocometary gas is not in the radiative regime, which could affect how well the methodology performed here models their properties. In the right panel of Fig. 3.5 a excitation diagram of three family D exocomets observed and analyzed by Vrignaud & Lecavelier des Etangs (2026). These gaseous clouds are located at different distances from the star, and as can be seen in Fig. 3.5 their level population distributions look different and follow the radiative regime model to a different degree. The level populations of comets 1 and 3 (blue and orange respectively in Fig. 3.5) seem to follow the 8200 K model well, especially for the low-energy levels. These two comets are transiting the LOS at short orbital distances of 0.88 AU and 1.52 AU respectively. The level population distribution of comet 2 (green in Fig. 3.5), which was transiting at 4.7 AU, does not follow the model well, the low excitation levels are over-populated and the high energy

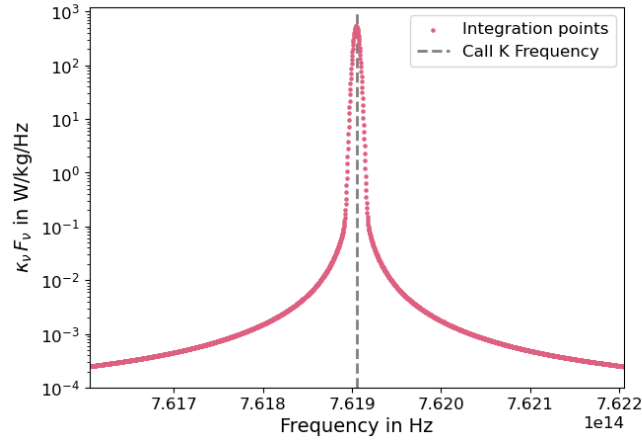


Figure 3.6: The quantity $\kappa_\nu F_\nu$ around the central frequency of Ca II K. As shown in the figure, the line is well resolved, with a large amount of sample points making up the peak. Due to this high point-resolution, a trapezoidal integration can be used to integrate in order to with high precision find the area under the curve.

levels are under-populated with respect to the prediction of the model. Fig. 3.5 shows that the radiative regime $T_{\text{ex}} \approx T_{\text{eff}} \approx 8000$ K assumption works best for comets transiting at very short orbital distances, but it also shows that the approximation is decent for intermediate distances, even up to 1.5 AU. Therefore, it is a reasonable assumption to make in order to model a significant portion of the exocomets in β Pic. It is also important to note that the orbital distance of exocomets is currently an active topic of research. Until recently, they were thought to all be transiting at very short distances to the star (Kiefer et al., 2014).

This methodology is different from the method used by previous studies. Beust et al. (1989) find the stellar flux of β Pic by interpolating between stellar flux values found for other stars of similar spectral type. They also calculate and sum the opacities of each relevant transition using the oscillator strength of the transitions. More recent studies by Fernández et al. (2006) and Lehtmetts et al. (2026) use model spectra. Additionally, both Fernández et al. (2006) and Lehtmetts et al. (2026) calculate the radiation pressure induced force manually using Einstein coefficients and statistical weights of energy levels, see Eq. (2.16). They assume that all of the gas is in the ground state transition, thus ignoring all transitions from higher energy levels, which could lead to the under-estimation of the radiation pressure induced force. By using a model spectrum and a full opacity function this work aims to produce a more exact value for the radiation pressure acceleration.

3.6.2 Photoionization Time-scales and Velocity Boosts

The photoionization time-scale of a species is the average time it can survive while being exposed to a flux level before being ionized. It is a property important for forming an understanding about the nature of gas released by exocomets and to understand observational results, such as the reason why NaI is observed much more rarely than CaII (Hoeijmakers et al., 2025). The photoionization time-scale is inversely proportional to the photoionization rate Γ , which was calculated using Eq. (2.18) which depends on the flux F_ν which the gas is exposed to and the photoionization cross-section of the species σ_ν .

The photoionization cross-section used was sourced from the Photoionization/Dissociation Rates (PhiDRATES) website (Huebner & Carpenter, 1979; Huebner et al., 1992; Huebner & Mukherjee, 2015). They were provided with the unit of cm^2 and as a function of wavelength. In order to match previous methodology, the cross-sections were translated onto a frequency space using $\nu = c/\lambda$. An example cross-section function for CaII is provided in the right panel of Fig. 3.4. Note that cross-sections of several species have significant sizes in the UV. The flux and cross-section models were used to find the ionization rate following Eq. (2.18)

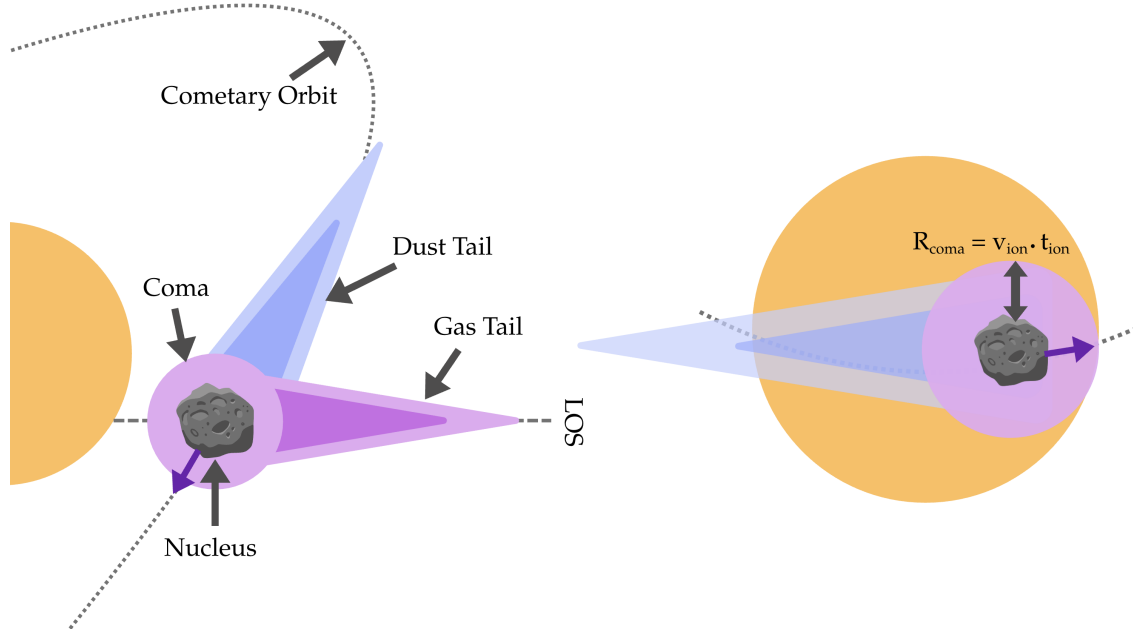


Figure 3.7: **Left panel:** A schematic showing the geometry of a comet on an orbit around a star. **Right panel:** A schematic showing a comet transiting the LOS. The radius of the coma can be estimated using the velocity boost of a species and its ionization lifetime.

The same trapezoidal integration method as described above was used to compute Γ .

Note also that the methodology used in this work is assuming that the atoms are in their ground state, this assumption is also used by [Fernández et al. \(2006\)](#). While it might be a good assumption for atoms located at a distance of 100 AU from the star, as is the case for investigating gas in the circumstellar disk done by [Fernández et al. \(2006\)](#), it is not a good assumption for the case of atoms in the gas released by exocomets, which is expected to be at a distance of $\sim 0.4 - 1.5$ AU. This assumption is still made here, due to the fact that a more careful analysis would require the inclusion of separate photoionization cross-sections for different states of ionization of each species, and the level populations would have to be calculated. Even though this is an interesting improvement to the methodology, it is outside of the scope of this thesis. Instead, the methodology presented here will provide the minimal photoionization rates and thus the upper limit of the photoionization lifetime of each species. The ionization rate estimation will likely also be limited by the frequency coverage of the model flux used. As shown in [Fig. 3.4](#), the cross-sections for several species investigated have high value in the far UV, this is discussed in detail in [Sect. 4.6.2](#).

Having obtained the photoionization rates Γ , the average lifetime of a species before ionization was calculated using $t_{\text{ion}} = 1/\Gamma$ and the velocity boost for the neutral atoms was calculated using [Eq. \(2.19\)](#). Having obtained the ionization time-scale and the velocity boost of the species, the expected size of the gas cloud formed from the sublimating exocomet was calculated. The velocity boost is the maximum velocity a particle will gain from being accelerated away from the star due to the radiation pressure. This is limited by the average time it takes for it to become ionized. From the two, a average, maximal cloud radius was calculated, see [Fig. 3.7](#) for a schematic of the comet geometry.

Chapter 4

Results and Discussion

In this section the results of this thesis are presented and discussed, starting with the results of the N-body simulation of the β Pic system. Note that many of the results presented here have been published in [Jaworska & Hoeijmakers \(2026\)](#), however this thesis presents additional unpublished analysis as well as a deeper discussion. [Sect. 4.1](#) presents the final outcome of the simulation and the fates of all test particles simulated are shown and discussed, leading to a conclusion that the β Pic system is in majority cleared as most test-particles are removed after 25 Myr of evolution. Two main regions are identified as exceptions, as they are stable on a time-scale that corresponds to the age of the system. They are labeled as the *inner region* and the *outer region*. Continuing, [Sect. 4.2](#) looks at the dynamical evolution of the simulated β Pic system over time and finds that most of the system below ~ 20 AU is cleared out on a short, Myr order time-scale. At late times (> 10 Myr) stargazers are seen to be continuously sourced from the two main stable regions identified. These are labeled *late stargazers* and studied more extensively in [Sect. 4.3](#) as they are the particles used to model the exocomets in β Pic today. The simulation shows that the exocomets in β Pic can be sourced from two different regions in the system and that the two populations have different properties which can be compared to observational results. The two populations are also expected to have compositional differences.

Limitations of the simulation are discussed in [Sect. 4.4](#) where it is highlighted that the results are strongly dependent on the choice of initial conditions and classification boundaries. Test of the sensitivity of the simulation to different choices are presented and discussed in [Sect. 4.5](#) where it is concluded that the main results are robust against the choice of planetary radii, maximal time-step and inclination distribution of the test particles.

Lastly, the results of the modeling of sublimated exocometary material are presented in [Sect. 4.6](#) where the computed β -factors and ionization time-scales are shown. The key finding of this modeling is that the ionization time-scale of NaI is on the order of 13 minutes, meaning that even though it gets a significant velocity boost from the radiation pressure, it is ionized before the NaI cloud can expand to observable sizes. The results point toward NaI only being observable if the exocomet is located far enough from the star or there are processes such as recombination and/or fragmentation that significantly increase the size of the NaI cloud.

4.1 Branching Ratios

As described in [Section 3.2.1](#), the simulated test-particles were classified based on a set of conditions that they could fulfill during the simulation. [Fig. 4.1](#) shows the branching ratios of the outcome of the classification at the end of the simulation, so after 25 Myr. It clearly shows that the majority of simulated test-particles are ejected from the system indicating that majority of the system is chaotic and dynamically unstable on a time-scale corresponding to the age of the system. Note that a large portion of the system, between about 1.5 to 21 AU, is completely cleared out after 25 Myr. The only regions where particles have

a non-negligible chance of surviving the full simulation without being removed can be identified in Fig. 4.1 by the grey color. These regions are:

- the region below 1.5 AU from the star,
- regions between ~ 20 and ~ 25 AU,
- the region beyond ~ 34 AU.

The first of the "stable regions" is the region below 1.5 AU. It is a region narrow in semi-major axis (about 1 AU wide) where $\sim 24\%$ of all particles initiated within this semi-major axis range survive the simulation. This is analogue to 24% of a primordial planetesimal disk surviving in this region close to the star, or that a single planetesimal that was located at this orbital distance would have about 24% chance of surviving until today. Even though this region of stability does not extend over a large semi-major axis range, it retains a significant portion of test-particles initiated there and could therefore be a potential planetesimal ring in β Pic today. Note that the inner edge of this region of stability is a consequence of the simulation set-up as no test-particles were initiated below 0.5 AU. This could result in an artificial cut-off of this region of stability. The region could extend even closer to the star. The choice of removal of test-particles that reach a periastron distance lower than 0.4 AU (see Section Sect. 3.2.1) is also limiting how close to the star this region of stability can extend.

Another interesting region is between ~ 20 and ~ 25 AU, where several regions of stability are present between low-order resonances with β Pic b, see Fig. 4.1. The fraction of particles surviving the simulation and being classified as stable is lower than for the close-in region of stability discussed above. About 5% of all test-particles initiated within this range are stable, meaning that a planetesimal on an orbit with a semi-major axis in between 20-25 AU would have a lower probability of surviving until today in this region of stability. However, these regions span over a larger range of semi-major axes and could together make up a possible planetesimal reservoir in the outer regions of the β Pic system, beyond the orbits of the two planets.

Finally, the last stable region identified by the simulation is the region extending beyond ~ 30 AU, where an increasingly large fraction of test-particles are classified as stable and after ~ 34 AU this fraction is 100% meaning that at orbital distances larger than this the system becomes fully dynamically stable on a time-scale that correspond to the age of the system. The dynamical influence of the two planets has not yet reached further than about 34 AU after 25 Myr of the systems evolution resulting in a planetesimal disk with an inner cavity that is truncated at this orbital distance and extending outward. The simulation shows that all test-particles initiated with semi-major axes larger than this limit are stable for the full duration of the simulation. Note that the simulation only investigated semi-major axes up to 45 AU so the results should be interpreted with this in mind as no ejected, stargazing or collided can be detected beyond 45 AU as there simply are none particles there to begin with. Given the results it is however highly unlikely that a non-negligible fraction of particles would be distorted by the planets at such large orbital distances, as the gravitational influence of the planets diminishes with distance. Note that due to the gravitational impact of the planets, the outer edge of this inner cavity will move outward over time, Rodet & Lai (2024) simulate the system for 10 Myr and report a cut-off distance of ~ 28 AU (see their Fig. 19) which is closer in due to the smaller simulation time.

The β Pic dust disk has been observed to have an inner cavity that is cut-off at ~ 50 AU (Dent et al., 2014; Matrà et al., 2019). The results of the simulation are in conflict with this observation. The observed cut-off of the inner cavity would correspond to a longer simulation time or to a more chaotic outer system. Lacquement et al. (2025) investigated this and showed that by including an additional planet, similar in mass to the systems two known planets, exterior to the orbit of β Pic b could place the cut-off at a orbital distance that better corresponds to the observed disk. They also demonstrate that the same is possible for several, less massive planets. As concluded by Lacquement et al. (2025), the theoretical planets they investigate are beyond the reach of current high-contrast imaging due to too low sensitivity making the system a good candidate for future observational campaigns with instruments of higher sensitivity. Matrà et al. (2019) also argue for the possible presence of a planet exterior to β Pic b due to observation of highly inclined planetesimals

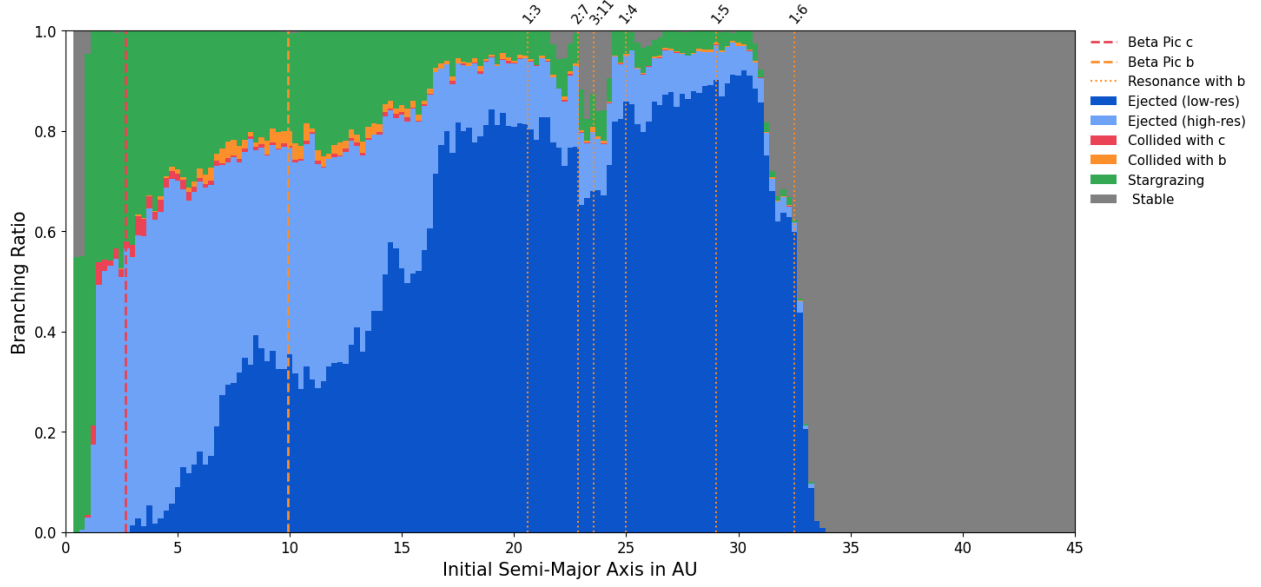


Figure 4.1: Branching ratios of the final classification of test-particles at the end of the simulation. The majority of all test-particles were ejected from the system (blue). A portion of ejections occur for particles on orbits that never reached a periastron distance lower than 3 AU and thus only have been simulated using the low time-resolution (dark blue). Remaining ejected particles have reached this periastron criterion and thus were simulated with the high time-resolution for some (or all) of the simulation (light-blue), see Section [Sect. 3.2.2](#) for a detailed explanation of the time-resolution used. A small fraction of the simulated test-particles did collide with either β Pic c (red) or b (orange). Green color represents stargazing particles and finally the fraction of particles that did not get removed from the simulation at all is presented in grey. Dashed lines indicate the semi-major axes of the planets and dotted lines are used to indicate resonances with β Pic b.

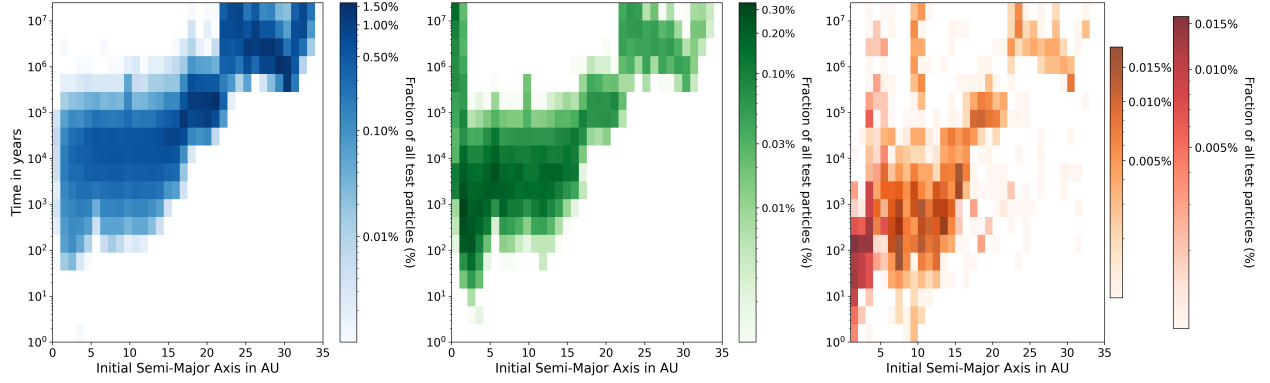


Figure 4.2: The classification of test-particles into ejected, stargrazing and collided particles over time. The panels show the fraction of all particles initiated within 35 AU which become removed from the simulation as a function of initial semi-major axis and time. **Left panel:** Ejected test-particles. **Middle panel:** Stargrazing test-particles. **Right panel:** collided test-particles. Particles collided with β Pic c and b are indicated in red and orange respectively, with two different color-bars for the two types of collisions.

in the outer disk.

The branching ratios presented in this thesis are consistent with previous work done by Rodet & Lai (2024) (their Fig. 19). Most of the system below ~ 20 AU is cleared out and does not have any stability on the simulated time-scales. The branching ratios agree about there being a cut-off to the outer edge of the inner cavity of the simulated disk, the difference in semi-major axis of this cut-off being explained by the different simulation times, the simulation presented here was run for more than twice as long than the one presented by Rodet & Lai (2024). Another major difference between the results presented by Rodet & Lai (2024) and the results presented here is the amount of test-particles seeded in the simulations. One of the primary aims of this work was to increase the amount of simulated particles to allow for more meaningful statistics and a higher semi-major axis resolution of the branching ratios, see Fig. 4.1. This allows for the reveal of features unseen by Rodet & Lai (2024) due to the low resolution of their branching ratios such as the two stability regions, within 1.5 AU as well as between 20 and 25 AU which become convincing when increasing the resolution of the branching ratios.

A simulation including a higher number of test-particles was performed by Beust et al. (2024). They do not provide a branching ratio of the different test-particle fates in their paper, however their Fig. 3 shows the eccentricity and semi-major axes of test-particles which survive ~ 10 Myr of their simulation. The results of Beust et al. (2024) are in agreement with the results of Rodet & Lai (2024) and of this thesis, as they show that the region between 1.5 and 20 AU is almost completely empty after 10 Myr of evolution. Their results indicate that on this time-scale, test-particles remain in two main different regions of the system: a region internal to the orbital distance of 1.5 AU, a region exterior to the orbits of the two planets, one outside of ~ 27 AU and also three belts in between 20 and 27 AU. In this way, the results of Beust et al. (2024) and the results of the study presented here are in strong agreement. As will be shown later, this study found that exocomets can be created from both of these regions while Beust et al. (2024) did only focus on the inner region, interior to 1.5 AU.

4.2 The Dynamical Evolution of β Pictoris

The branching ratios discussed in Sect. 4.1 only show the final outcome of the simulation, they do not provide any insight about the evolution of the simulated disk of test particles. In order to make any statements about the dynamical evolution of a model primordial planetesimal disk around β Pic, the branching ratios should be studied as a function of time. The two left panels of Fig. 4.2 shows the fraction of test-particles initiated

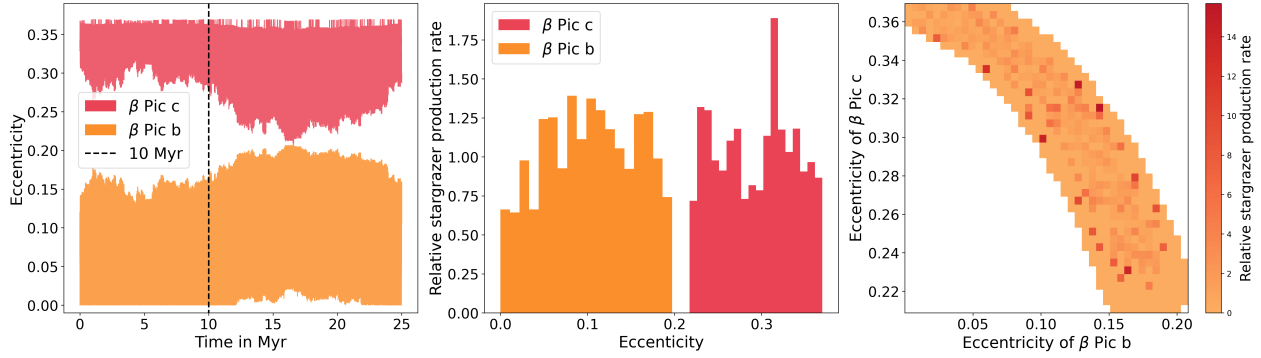


Figure 4.3: **Left panel:** The eccentricity evolution of β Pic b and c over time. **Middle panel:** The relative rate of stargrazer creation in the last 10 Myr of simulation as a function of the eccentricity of the two planets individually. In the figure, 1 is the average production rate, eccentricities that have a relative rate larger than one produce more stargazers than the mean. **Right panel:** The relative rate of stargrazer creation in the last 10 Myr of the simulation as a function of the eccentricity of β Pic c (y-axis) and β Pic b (x-axis).

within 35 AU that become classified as ejected (left panel) and stargazing (middle panel) as a function of time and initial semi-major axis. These figures show that the inner system, between 1.5 and ~ 20 AU is emptied on a time-scale of ~ 1 Myr, corresponding to less than one tenth of the systems lifetime. This shows that the majority of the inner system is highly chaotic and dynamically unstable on short time-scales making it impossible for a primordial planetesimal reservoir to be retained there under the current known system properties. In several previous studies, the exocomet reservoir was assumed to be located at a semi-major axis in the region between the two planets, see Sect. 2.4. This was the leading theory until the discovery of β Pic c, which complicated the system. The work presented here agrees with the predictions of Rodet & Lai (2024) and Beust et al. (2024) that simulate the system with the inclusion of the recently discovered β Pic c (Lagrange et al., 2019): the region between 1.5 AU and ~ 20 AU is not dynamically stable on a time-scale corresponding to the age of the system.

The rightmost panel of Fig. 4.2 shows the fraction of particles classified as collided as a function of time and initial semi-major axis. The evolution of particles that collide with the planets looks slightly different than the evolutions of ejected particles and stargazers. Particles keep colliding with the planets for a long time, until the very end of the simulation. This is due to the possibility of particles being captured in the Hill sphere of either of the planets. The particles captured survive in the inner system for longer than the vast majority of the test-particles initiated at similar semi-major axes, until they eventually collide with the planet. Increasing the semi-major axis resolution of Fig. 4.1 reveals that the planets actually maintain a small fraction of stable particles close to them. Thus, the inner system is dynamically unstable however there is a non-zero possibility of planetesimals to survive the evolution of the system if they are originally positioned on an orbital distance that is close to either of the planets. This result could be interpreted such that the simulations predict the possibility of the two planets in β Pic having moons. The simulation only shows that if there were planetesimals in the Hill sphere of the planets 25 Myr ago, they could have been retained by the planets until today. The simulation does not predict tidal forces, collisions or any other possible mechanisms that could distort said planetesimals. These mechanisms could have a significant effect on the planets ability to retain moons. Note also that the number of collided particles is significantly smaller than the number of ejected and stargazing particles, meaning that the evolution here is statistically less significant. This simulation was not designed with collisions and the formation of potential satellites of the planets in mind. It does however show a promising initial result, opening up for the possibility of future studies investigating this in more detail.

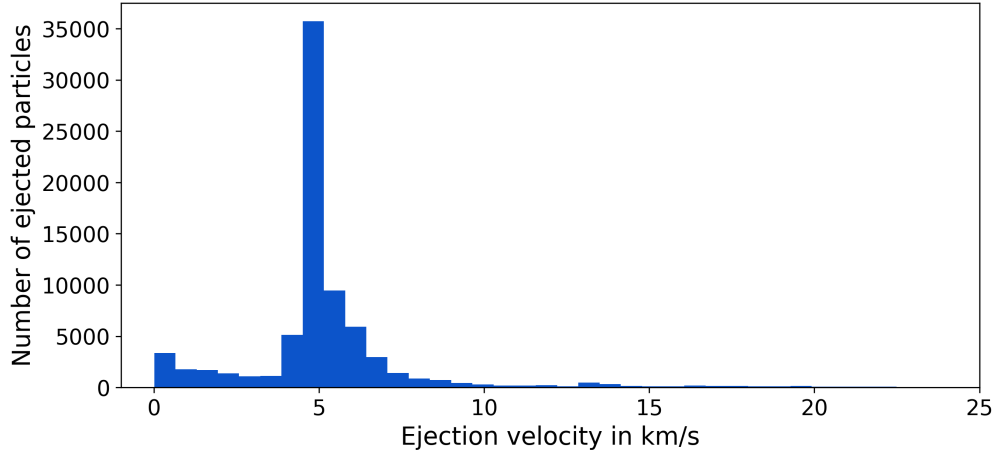


Figure 4.4: Ejection velocity of all test-particles classified as ejected from the system.

4.2.1 Dependence on the Planetary Eccentricities

Fig. 4.3 shows the evolution of the eccentricity of the two planets in the left panel. Due to the perturbations of the planets onto each other, their eccentricity varies with time. They seem to have a non-regular variation with time, which is a consequence of the planets being in a hybrid 7:1 MMR (Beust et al., 2024). The middle panel of Fig. 4.3 shows the relative stargrazer production rates as a function of the eccentricity of the two planets evaluated individually. The production rate has been normalized such that a value of one corresponds to the average production rate. Thus, if at a specific eccentricity the system is producing less stargrazers, the relative production rate is smaller than one at that eccentricity. For the case of β Pic b, this is true for low eccentricities, see middle panel of Fig. 4.3. If the system produces more than an average amount of stargrazers at a certain eccentricity, this eccentricity will have a production rate larger than one, this happens for $e_c \approx 0.31$ for β Pic c. The right panel of Fig. 4.3 shows relative production rate as a function of the eccentricity of the two planets evaluated together. As can be seen in the figure, the eccentricities are anti-correlated with each other. Some spots of increased stargrazer activity can be identified in the figure, however they are most likely noise. By evaluating the relative stargrazer rate as a function of eccentricity, both for each planet individually and together, no meaningful conclusion can be drawn. The stargrazer production rate after 10 Myr seems to not be dependent on the eccentricity variation of the planets. Note that this test is based on a limited sample of stargrazers that get classified as such after 10 Myr, this sample is discussed more in detail in Sect. 4.3. Including a larger sample could reveal smaller eccentricity dependencies. For example, it could determine if the $e_c \approx 0.31$ peak is meaningful, or just a noise artifact. Note that only stargrazers created after 10 Myr were included in Fig. 4.3, due to two reasons. Firstly, as discussed in later sections of the thesis, these stargrazers are particularly interesting as they model exocomets observed in β Pic today. Secondly, the inclusion of particles identified as stargrazers earlier on in the simulation skewed the distributions presented in Fig. 4.3, as an overwhelming majority of stargrazers are classified at early time-scales, see Fig. 4.2.

4.2.2 Ejection Velocities

Every particle that was classified as either stargazing, collided or ejected was removed from the simulation, and its last orbital parameters were saved. From the orbital parameters, its cartesian coordinates were recovered, including the velocities v_x, v_y, v_z . Fig. 4.4 shows the total ejection velocity $v_{ej} = \sqrt{v_x^2 + v_y^2 + v_z^2}$ of all test-particles classified as ejected in the simulation. There is a distinct peak in the distribution, at ~ 5 km/s. The simulation predicts that the vast majority of planetesimals would leave the β Pic system with this velocity while only a few outliers leaving with smaller or higher velocities. Note that the simulation only includes gravitational interactions between the test-particles and the massive bodies of the system, therefore

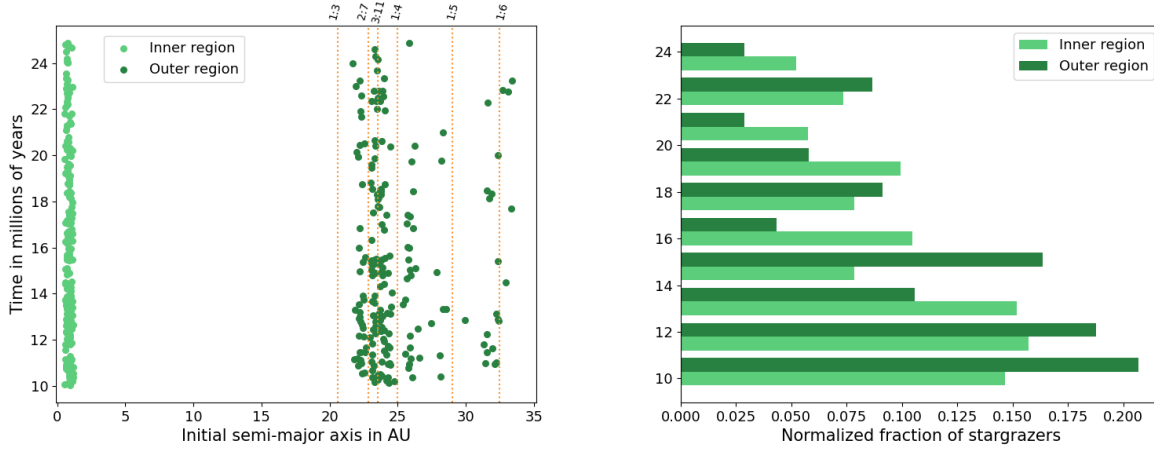


Figure 4.5: **Left panel:** The figure shows the last 15 Myr of the simulation and particles which are classified as stargrazers after 10 Myr of the simulation time. These particles are referred to as *late stargrazers* and are modeling the exocomets observed in β Pic today. They can be seen originating from two main regions the *inner region* (below 1.5 AU) and the *outer region* outside of 20 AU. **Right panel:** The normalized fraction of stargrazers created from each of the two regions as a function of time.

planetary scattering is the reason for the ejection. The resulting ejection velocities compare well with ejection velocities due to planetary scattering found by previous studies (Adams & Spiegel, 2005; Pfalzner et al., 2021).

Interestingly, there exists a family of meteoroids in our solar system that are in a collimated stream which has been traced back to and is thought to originate from β Pic (Baggaley, 2000). It is called the β Pic dust stream. Krivova & Solanki (2003) and Krivov et al. (2004) investigated possible ejection mechanisms and concluded that the most likely source of the β Pic dust stream is a major event which happened ~ 0.7 Myr ago and caused an increased ejection rate from the system. The meteoroids that are attributed to the β Pic dust stream are predicted to have left the system on ejection velocities on the order of ~ 25 km/s (Krivov et al., 2004), which is significantly larger than the average ejection velocities predicted by the simulation performed here. The β Pic dust stream is therefore likely not related to the particles ejected from the system due to scattering of the systems two known planets. Another ejection scenario investigated by Krivov et al. (2004) was radiation pressure ejecting dust released by exocomets, which is an interesting possibility as it would mean that the exocomets of β Pic, or at least their fragments, are in our solar system.

4.3 Two Populations of Exocomets

Tracking the dynamical evolution of the system over time is useful to understand how a primordial planetesimal disk might have evolved over time and how structures in today's β Pic system were created. However, in order to draw parallels between the simulation results and the observations of exocomets in β Pic, the last 15 Myr of the simulation were investigated more extensively. The left panel of Fig. 4.5 shows the last 15 Myr of the systems evolution. Particles which are identified as stargrazers at a time later than 10 Myr from the start of the simulation are shown. From this point onward, these will be referred to as *late stargrazers*. Late stargrazers are particles which cross the exocomet observability threshold, a periastron distance of 0.4 AU, at a time-scale that is on the same order of magnitude as the age of the β Pic system and therefore could model the exocomets observed in the system today. Fig. 4.5 presents their initial semi-major axes and shows at what time they became classified as stargrazers, so at what time in the simulation their orbits reached a periastron distance smaller than 0.4 AU. Resonances with β Pic b are indicated with dotted lines, equivalent to Fig. 4.1.

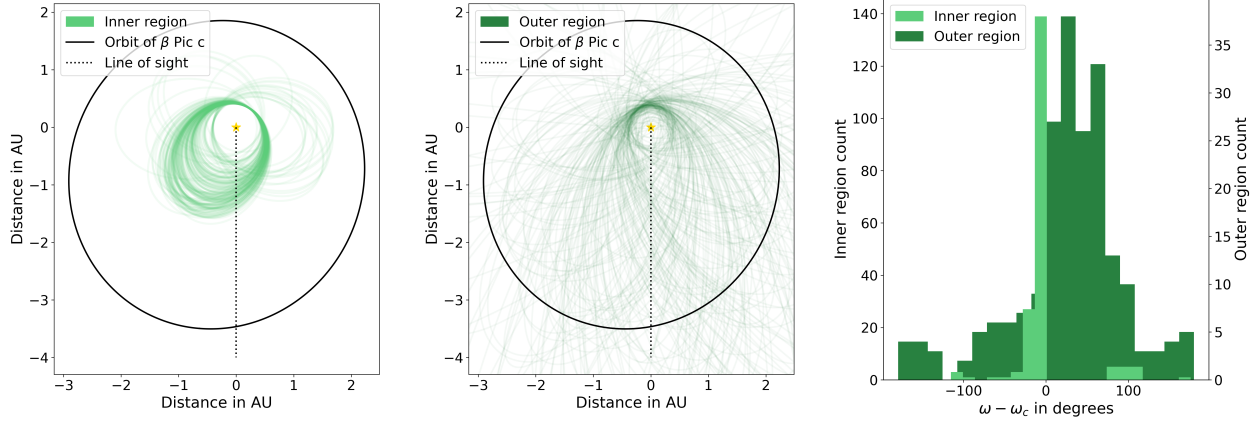


Figure 4.6: The orbital alignment of late stargrazers in comparison to β Pic c. **Left panel:** The orbits of inner population stargrazers shown together with the orbit of β Pic c. **Middle panel:** The orbits of outer population stargrazers shown together with the orbit of β Pic c. **Right panel:** The distributions of $\Delta\omega = \omega - \omega_c$, the difference between the arguments of periastron stargrazers' and β Pic c, showing a strong correlation for the inner population stargrazers. Stargrazers from the outer population show a moderate alignment with β Pic c.

A total of 399 late stargrazers were produced in the simulation. There is a clear division between two regions of origin of late stargrazers as seen in Fig. 4.5. One population of late stargrazers originates in the vicinity of the star, from a region smaller than ~ 1.5 AU, while a second population originates from a broader region between $\sim 20 - 25$ AU as well as around 30-32 AU. Out of the 399 late stargrazers produced by the simulation, 191 corresponding to $\sim 48\%$ originate from the inner system while the remaining $\sim 52\%$ (208) late stargrazers originate in the outer system. Note that no prediction can be made for the creation rate of exocomets from the two regions, as this is dependent on the initial distribution of test-particles. The relative fraction of stargrazer origin would change if the initial distribution of test-particles was changed from a uniform distribution as described in Sect. 3.2, to any other distribution. A more informed distribution has to be adopted in order to be able to draw any conclusions about relative exocomet creation rates.

The normalized fractions of late stargrazers created from each of the two regions are shown in the right panel of Fig. 4.5. The rate stargrazer creation is generally decreasing over time from both regions, indicating that the frequency of exocomet production in β Pic was higher millions of years ago as the reservoirs were more populated. With time, the reservoirs are continuously emptied and the rate of stargrazers produced therefore goes down. The sole production of stargrazers from these region is an indication of the fact that perturbations from the planets is slowly emptying them. These regions will likely not exist forever, however a follow-up simulation would have to be performed in order to constrain the exact lifetime of the proposed exocomet reservoirs.

4.3.1 Distributions of Radial Velocities

Upon further investigation of the late stargrazers sourced from the two different regions in the system, the results point toward the two populations also undergoing different dynamical evolution on their way to becoming exocomets. Fig. 4.6 shows the alignment of the orbits of late stargrazers compared to the orbit of β Pic c. The right panel shows the angle difference between the argument of periastron of the stargrazers and planet c $\Delta\omega = \omega - \omega_c$, while the two panels to the left show the orbits of stargrazers from the inner region (left panel) and the outer region (middle panel). Late stargrazers from the inner region seem to be well aligned with the orbit of β Pic c as there is generally just a small difference between their argument of periastron and that of the planet. This indicates that the orbits of these particles were excited by MMR with β Pic c, resulting in a very aligned set of orbits. The late stargrazers originating from the outer region have

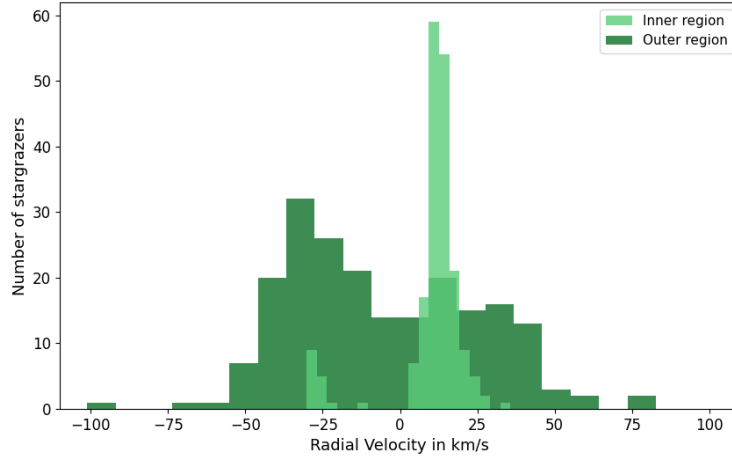


Figure 4.7: The resulting radial velocity distributions of late stargrazers from the two populations identified in the simulation. The inner population stargrazers have a narrow RV distribution centered on 13 km/s with a standard deviation of 4 km/s, while stargrazers from the outer population have a broader RV distribution. These results are RV predictions from the simulation, this figure can be compared to observational results in Fig. 2.5 (rightmost panel).

a more scattered distribution of orbits, reflecting a more complex creation mechanism which brought these particles from a large initial orbital distance to the vicinity of the star. Note that even stargrazers from the outer system seem to have a moderate alignment with the orientation of the orbit of β Pic c, see right panel of Fig. 4.6. The LOS has been placed at the $-y$ -axis using the convention of Green (1985), following Lacour et al. (2021). The radial velocity distributions of the late stargrazer populations were evaluated, see Fig. 4.7. Also note that the coordinate frame of all stargrazers has been rotated to match the current orbit of β Pic c, meaning that if any of the orbits would align with the directionality of β Pic b, this would have been washed out in these results. β Pic b does have a smaller eccentricity than β Pic c and the later has been shown to be especially important in the process of creating stargrazing particles (Rodet & Lai, 2024). This feature would only affect the stargrazing particles from the outer population.

By defining a LOS, the radial velocities of the simulated exocomets could be extracted. This was done by retrieving the velocity along the y -axis, see Fig. 4.6. The resulting RVs of the simulated exocomets are shown in Fig. 4.7. The two populations have distinctively different RV distributions. The inner population exocomets are by the simulations predicted to be observed in a narrow and peaked distribution of RVs, centered at 13 km/s with a standard deviation of 4 km/s. This corresponds well to one of the observed families of exocomets in β Pic. Kiefer et al. (2014) measured a RV distribution of 15 ± 6 km/s for the D-family, see Fig. 2.5. Therefore, the results of this thesis conclude that at least one of the exocomet families in β Pic could originate from a reservoir in the vicinity of the star, located at an orbital distance below 1.5 AU, and be dynamically driven onto stargrazing orbits through MMR with β Pic c. This conclusion is also in line with simulations done by Beust et al. (2024) who also point out the same region and production mechanism as a plausible explanation behind the exocomet phenomenon of β Pic.

While Beust et al. (2024) use only one source and creation mechanism to explain all observations of exocomets in β Pic, the results of this study point to a different conclusion. The RV distribution of inner region stargrazers is very narrow, and could not explain exocomets observed at high velocities of even up to hundreds km/s. Instead, the simulation shows that a second population, the outer population, could explain exocomets observed at high radial velocities. From Fig. 4.7 it is clear that stargrazers from the outer region have a broad distribution of radial velocities, that is ranging from ~ -50 km/s to $\sim +50$ km/s. It could therefore

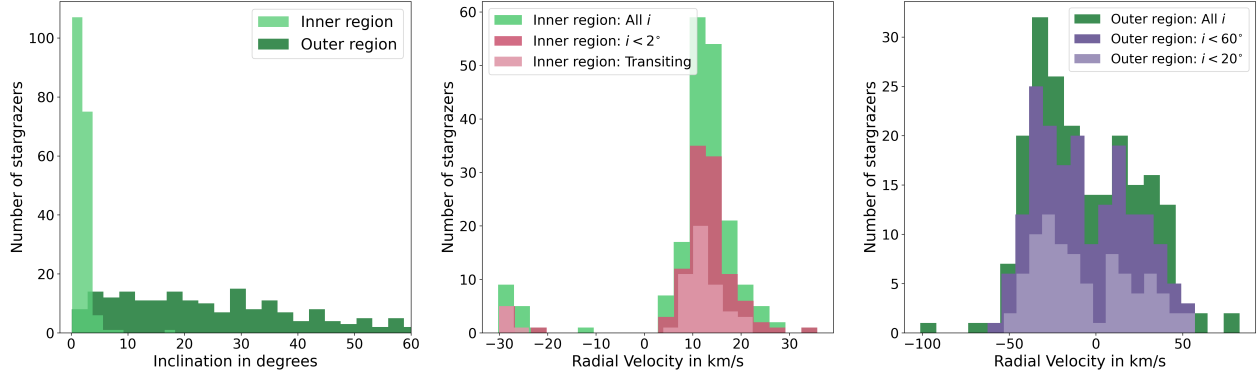


Figure 4.8: **Left panel:** The distributions of orbital inclinations from edge on orbit ($90^\circ - i$) of stargrazers from the inner and outer populations. Note that this panel shows inclinations up to 60° , leaving out $\sim 13\%$ of particles from the outer population. **Middle panel:** The RV distribution of the inner region stargrazers shown for different limiting inclinations. **Right panel:** The RV distribution of stargrazers from the outer region shown for different limiting inclinations.

be comparable to the second family found by Kiefer et al. (2014), family S. Even though the simulations predict two different families of exocomets, which is consistent with observations, the RV distribution of the outer family in particular deviates from the shape of the observed S family, see the rightmost panel of Fig. 2.5. The simulation predicts that the majority of outer population stargrazers will have blue-shifted RVs. Instead, the majority of the S family exocomets have been observed in red-shifted RVs. The misalignment between the simulated and observational results could arise from limitations of the simulation, which will be discussed in the next section.

The simulation only produced 399 late stargrazers, a limited sample. Many of them were found on inclined orbits, see the left panel of Fig. 4.8. Note that the figure shows inclination from edge-on orbit, so $(90^\circ - i)$. While it is conventional to use 90° to denote edge-on orbit in the field of exoplanetary science, an orbit that is in the rotational plane of the star has a 0° inclination in REBOUND. Therefore, in this context and in Fig. 4.8 a 0° inclination means a completely edge-on orbit. Many of the late stargrazers do not transit as they have high inclinations and impact parameters larger than 1. As can be seen in Fig. 4.8, stargrazers from the inner region typically have low inclinations, and approximately 25 % of them do transit. The number of transiting stargrazers from the outer population is much smaller, around 2%, as particles from the outer region have a broad distribution of inclinations. The simulation shows that particles initiated outside the orbits of the systems two planets can enter the inner system and become stargrazers while being on highly inclined orbits. It is interesting, as the simulation was initially seeded with particles on nearly edge-on orbits, with inclinations ranging between 0° and 2° , meaning that the interactions necessary to migrate the particles into the inner system and stellar vicinity also increased their orbital inclinations. Therefore, the nearly edge-on orientation of β Pic does not have to be a requirement for the observation of exocomets and bodies like these could be found in inclined systems, such as the planet forming PDS 70, where exocomets were recently discovered (Novais et al., 2025).

Even though most late stargrazers do not transit the LOS, they were all still included in the analysis of the RV distributions. They were all included in order to obtain meaningful statistics. Stargrazers on orbits with impact parameters larger than one were included in the analysis by the evaluation of their velocity in the direction of the star, $v_{\text{rad}}^2 = v_y^2 + v_z^2$, instead of simply using the y -component velocity as described above. If the radial velocity was evaluated using just the v_y component, the RV distributions would become biased to smaller values as particles that cross the transit center at a large angle have will have a smaller v_y component than the same particle crossing the transit center in the plane.

In order to test if the inclusion of stargrazers on non-transiting orbits affects the shape of the RV distributions,

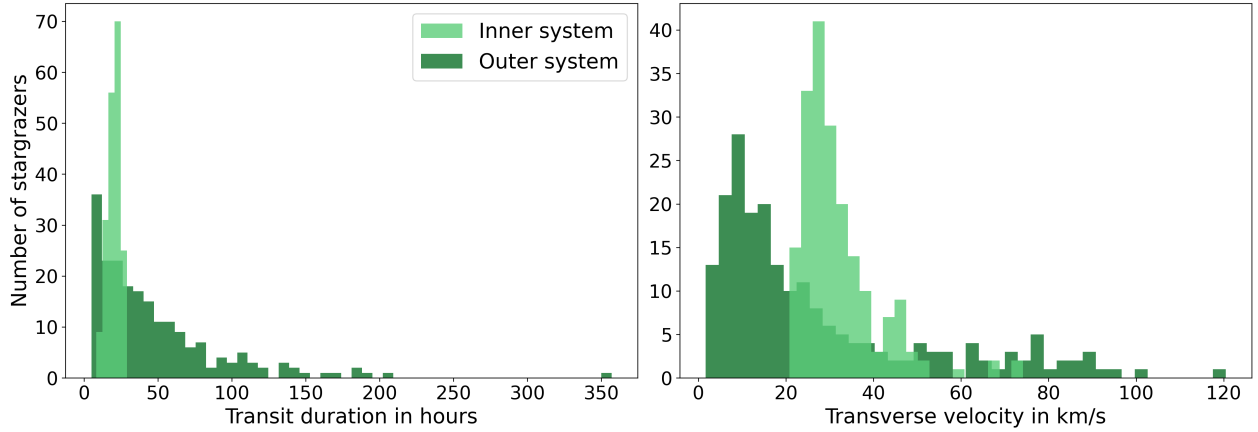


Figure 4.9: Transit properties of the late stargrazers identified from the simulation. **Left panel:** The predicted transit duration of the two exocomet populations, both observable as their transit duration is generally longer than a few hours. **Right panel:** The predicted transverse velocity.

the stargrazers were divided into groups based on their inclination and their RVs were evaluated separately, see Fig. 4.8. For the inner population of stargrazers, even if there was a bias it would have been low as their inclinations are on the order of a few degrees only. In the middle panel of Fig. 4.8 the RV distributions of the inner region stargrazers are shown for all stargrazers as well as the RV distribution of only the particles limited to smaller inclinations ($i < 2^\circ$) and a RV distribution of only transiting stargrazers. All three RV distributions have similar shapes, and thus the inclusion of inclined particles does not seem to bias the RV distribution. Similarly, only including particles with smaller inclinations from the outer region does not seem to change the RV distribution, see the right panel of Fig. 4.8. Here, the full outer population was compared to the RV distributions of particles with inclinations smaller than 60° and 20° respectively, showing no signs of bias being introduced with the inclusion of higher inclinations. Note however that only a handful of stargrazers from the outer region transit and therefore the RV distribution of transiting particles from this population was not meaningful and could not be used for comparison.

4.3.2 Transit Properties

From analyzing the orbits of late stargrazers, see Fig. 4.6, the observational properties of transit duration and transverse velocity of the stargrazers could be derived from them, see Fig. 4.9. The left panel shows the predicted transit duration, which is the time between the first appearance of the exocomet in the LOS and the time it leaves the LOS. In practice, it is the width of the transit light-curve and also dictates how long an absorption feature from an exocomet would be visible in the spectrum of β Pic. Stargrazers from the inner population have transit durations that are on the order of 18 hours. Observations of exocomets in β Pic show that the spectral features are variable on a day-to-day basis and that features typically remain stable for the duration of one night (Kiefer et al., 2014). A few features have been observed to change their RV during the night and their acceleration was measured (Kennedy, 2018; Hoeijmakers et al., 2025). A large portion of outer population stargrazers also have short transit durations of around 18 hours, however some of them have very long transits, that last for several days. There have been reports of exocometary absorption features that are stable on long time-scales, for example a feature that persisted for 13 nights (Hoeijmakers et al., 2025). Based on the results of the simulation performed here, it is more likely that this exocomet originated in the outer system.

The transverse velocities of late stargrazers are another property that is predicted by the simulation, see the right panel of Fig. 4.9. Particles from the inner population have a transverse velocity distribution that peaks at around 30 km/s, and extend up to between 60 km/s and 80 km/s. They also have a sharp lower cut-off at almost exactly 20 km/s. This lower bound is expected, as particles from the inner region are confined

to an orbital distance which is dictated by the inner stability region, see Fig. 4.1. Particles cannot have a lower orbital velocity because they are limited to a maximal orbital distance. Particles located outside of the ~ 1.5 AU stability boundary would with high probability not survive for long enough to be considered in this analysis. For a particle on a circular orbit, the orbital speed at a semi-major axis of 1.5 AU is:

$$v_{\text{circ}} = \sqrt{\frac{GM}{a}} \approx 32 \text{ km/s}, \quad (4.1)$$

where M is the mass of the star, assumed to be $1.77 M_{\text{Sun}}$ as in T. 3.1. The circular cut-off velocity is around 30 km/s, however the inner population stargazers are not on circular orbits. In fact, their orbits are highly eccentric, with a mean eccentricity of ~ 0.5 . The LOS cuts the orbits at a place which is closer to the apastron of the orbits, meaning that the orbital speed in that point of the orbit will be smaller than v_{circ} . At apastron $r_{\text{apo}} = a(1 + e)$, the velocity will be:

$$v_{\text{apo}} = \sqrt{GM \left(\frac{2}{a(1 + e)} - \frac{1}{a} \right)} \approx 19 \text{ km/s}, \quad (4.2)$$

assuming $a = 1.5$ AU and $e = 0.5$ (de Pater & Lissauer, 2015). Accounting for that and the fact that the transversal velocity is equal to the orbital velocity minus the radial and vertical velocity components $v_t^2 = v_{\text{orb}}^2 - v_r^2 - v_z^2$, confirms that the 20 km/s cut-off is expected for the inner system stargazers.

The transverse velocity distribution for particles from the outer region peaks at a lower value of ~ 10 km/s, but a few stargazers from this family are predicted to reach transverse velocities that are higher than 80 km/s. The deep transit event reported by Zieba et al. (2019), see Fig. 2.4, was measured to have a transverse velocity of 19.6 ± 0.1 km/s. This is just below the cut-off velocity of the inner region and could indicate that the exocomet observed by Zieba et al. (2019) was originating from the outer region. Even though the first photometric observation of an exocomet was made in 2019, it started a trend. Several surveys have been performed where archival data from instruments such as TESS and K2 are used to search for exocomets around new stars (Dumond et al., 2025; Norazman et al., 2025). The results of this thesis provide predictions for distributions of transit duration and transverse velocities that could be compared with future observational results in a similar way as it was done for the RV distribution above, if the scale of the photometric observations of exocomets in β Pic reaches comparable levels to a similar scale of spectroscopic observations. Note however that photometric observation requires a large amount of dust production which might introduce a bias to the observations.

4.3.3 Compositional Differences

A key unanswered question about the exocomets of β Pic is their composition and whether they are volatile rich and icy, like solar system comets, or rocky and devolatilized, resembling solar system asteroids (Beust et al., 1989; Beust et al., 1990; Wilson et al., 2017; Beust et al., 2024; Vrignaud et al., 2024; Kenworthy et al., 2025). Exocomets have been primarily observed in lines of refractory ions, most prominently CaII (e.g. Ferlet et al., 1987; Kiefer et al., 2014), while volatile species commonly present in solar system comets have so far not been successfully detected in the exocomets of β Pic (Kenworthy et al., 2025). Even without any direct proof of volatile content, the morphology of β Pic exocomets have previously modeled by assuming icy compositions (Kiefer et al., 2014), where calcium released from the cometary surface as part of a volatile-rich and spectroscopically invisible outflow. In contrast to results presented by Beust et al. (2024) who conclude that all of the system's exocomets must originate in the inner system and thus be primordially devolatilized, the results of this thesis make the prediction that the exocomets in β Pic could be sourced from two different regions in the system. A portion of the exocomets observed in β Pic could thus be volatile rich in composition.

As a result from the simulation, two different populations of late stargazers were identified. They originate in reservoirs that are located at vastly different orbital distances, they are expected to have a different primordial composition. The inner region is located close to the star, where temperatures are well over 500 K and the planetesimals in this reservoir are expected to be primordially devolatilized. However, planetesimals

in the outer region should contain volatiles, as this reservoir is located outside of the water ice line of the system, which is estimated to be at 8.2 AU (Lodders, 2003), see Sect. 3.4. Even though the outer population planetesimals are volatile rich when they are in their reservoir, it is not certain that the late stargazers that are used to model the exocomets of β Pic still contain volatiles as they graze the star. They must migrate from the outer system into the vicinity of the star and depending on how long they spend migrating, their volatile content might vary.

Fig. 4.10 shows how long the outer region stargazers spend within the water ice line of the system while migrating from the outer system into the vicinity of the star. During this time, the ice contained in the planetesimals would be gradually sublimated. The particles generally migrate efficiently through the system, most of them spend on the order of 10^2 to 10^3 years inside of the water ice line, before reaching the 0.4 AU periastron criterion and being classified as a stargazer. A study performed by Karmann et al. (2001) modeled the sublimation of ice in β Pic exocomet progenitors. They found that the sublimation rate varies depending on the size of the body, the distance to the star and on the composition of the body. A body made up of pure ice sublimates very efficiently and therefore has a very low lifetime. Karmann et al. (2001) found that the sublimation of ice contained within porous bodies is less effective. Ice was found to survive in porous, 1 km sized bodies, closer than 5 AU from the star, on a time-scale longer than 10^5 years. This is much longer than the time-scale the stargazers spent outgassing, see Fig. 4.10, meaning that significant amounts of ice could still be contained in the bodies as they graze the star and are observed as exocomets. The results of this study suggest that stargazers from the outer population might be rich in volatiles.

Possible differences in the composition of exocomets from the two families were reported by Kiefer et al. (2014), who report that the two families not only have different RV distributions but also tend to have different surface fractions of the stellar disk, see Fig. 2.5. Exocomets from family S generally cover smaller parts of the stellar disk, indicating a lower evaporation rate due to devolatilization of the comets from this family. Family D exocomets exhibit larger fill fractions, indicating a higher dust evaporation rate as a result of a higher volatile content. The results of the simulation performed for the purpose of this thesis are in conflict with the results by Kiefer et al. (2014). The two studies arrive at two opposite conclusions regarding the compositional difference between the two exocomet populations.

Based only on the RV distributions, the inner population of stargazers corresponds to family D exocomets as reported by Kiefer et al. (2014) and the outer population corresponds better to the S family. Kiefer et al. (2014) arrive at the conclusion that family D must be volatile rich, while family S devolatilized. However, the results presented in this study show that the inner population must be primordially devolatilized while the outer population might be rich in volatiles. The different conclusions might be explained by different assumptions about the β Pic system. Kiefer et al. (2014) attributed the wide RV distribution of family S to MMR with β Pic b. After the discovery of β Pic c, the simulations done by Rodet & Lai (2024), Beust et al. (2024) and this thesis show that the MMR claimed to be responsible for the creation of family S exocomets by Kiefer et al. (2014) are not possible, as that region of the system is highly dynamically unstable on short time-scales. Instead, new simulations show that the RV distribution of family D can be reproduced by MMR with β Pic c (Beust et al., 2024) and also confirmed by results from this thesis. Both these studies require the reservoir of family D exocomets to be located interior to the orbit of β Pic c, at an orbital distance of at most 1.5 AU, where temperatures are higher than 500 K. This means that family D exocomets (inner region stargazers) are expected to be primordially devolatilized.

Recently, Vrignaud & Lecavelier des Etangs (2026) measured transit distances of three exocomets observed to have low radial velocities. They found larger transit distances than previously predicted Kiefer et al. (2014); Kennedy (2018). Two of the comets they investigated were found to have a transit distance of 0.88 AU and 1.52 AU respectively. These distances fit well into the predictions of the inner population stargazers, which are expected to be transiting at distances of up to ~ 1.5 AU, see Fig. 4.6. The third comet studied by Vrignaud & Lecavelier des Etangs (2026) was measured to be transiting at a distance of 4.7 AU. It is significantly larger than any other transit distance ever measured. The stargazers from the outer population are expected to have a wide range of transit distances, see Fig. 4.6 and therefore this exocomet could originate

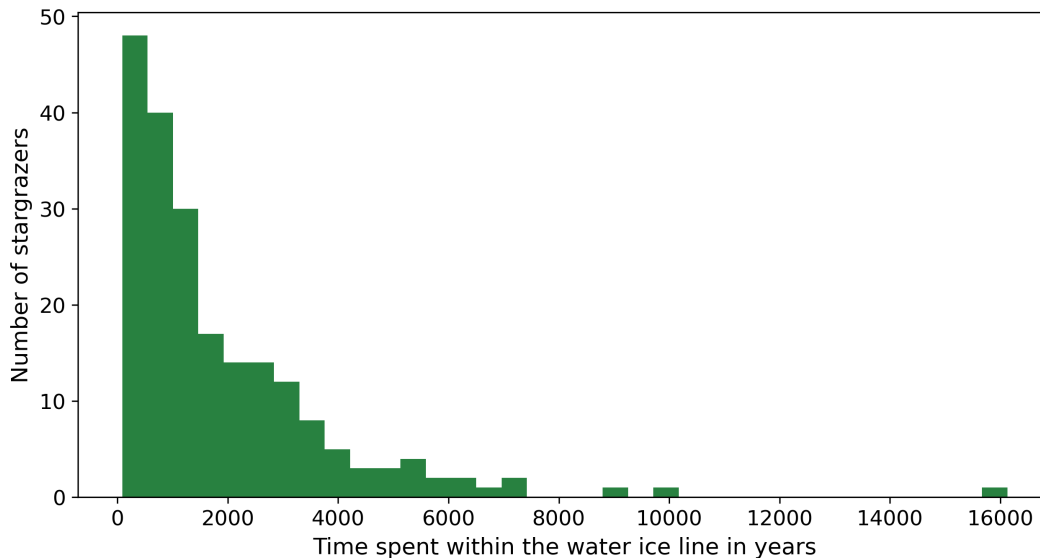


Figure 4.10: The cumulative time the outer population exocomets spend within the water ice line of the β Pic system while they are migrating from the outer system to the vicinity of the star. The water ice line is estimated to lie at 8.2 AU (Lodders, 2003). The time-scale shown here corresponds to the time the particle spends between 8.2 AU and 0.4 AU, periods during which the particle resides at distances $r > 8.2$ AU are not included.

from the outer system. Vrignaud & Lecavelier des Etangs (2026) claim to be studying family D exocomets as they are looking at low RV events, however exocomets from family S have also been detected at low radial velocities, see Fig. 2.5. This is also the case for the predicted RVs of the outer population, see Fig. 4.7. Therefore, the third comet observed by Vrignaud & Lecavelier des Etangs (2026) might not be a family D exocomet but could instead belong to the family with a broad RV distribution, family S.

4.4 Simulation Limitations

The simulation performed in this work predicts the existence of two distinct populations of β Pic exocomets with different dynamical properties, originating from different reservoirs in the system. This is the first time that the presence of two exocomet families has been recovered by theoretical work, even though the presence of two exocomet families has been an observable fact for over ten years (Kiefer et al., 2014). Even though the simulation accurately predicts the RV distribution of one observed exocomet family, family D corresponding to the inner population of stargazers simulated here, the predicted RV distribution for the second family does not match the observations equally well. When comparing between the observational results, Fig. 2.5, and the simulation results, Fig. 4.7, the population that exhibits a broad RV distribution does not have the same shape. The simulations predict a larger amount of blue-shifted events compared to the observations. This discrepancy could be a result of the limitations of the simulation, which are discussed below.

First of the simulation limitations is the way that particles are being identified as stargazers. The criterion for being classified as a stargazing particle is that the orbit of a test-particle has a periastron distance which is smaller than 0.4 AU when the particle is located at a distance less than 1 AU from the star, see Sect. 3.2.1. Upon classification, the particle is removed from the simulation. Therefore, the simulation does not capture any orbital evolution after the criterion was fulfilled once. Further orbital evolution could lead the particle onto an orbit that gets closer to the star, allowing for a larger velocity. This limitation could explain why stargazers from the outer population are limited to low RVs, while the corresponding observed exocomet family includes exocomets with RVs of hundreds of km/s (Kiefer et al., 2014). The 0.4 AU periastron limit

is grounded in work by [Beust et al. \(1998\)](#) who argue that the evaporation rate of CaII is large enough to be observable at this distance. It is however possible that exocomets become observable at distances larger than 0.4 AU. A more inclusive stargrazer criterion would result in a lower cut-off transversal velocity of the inner population.

Furthermore, a test-particle can only be classified as a stargrazer once. The simulation does not model the possibility of an exocomet being observed twice. It is currently not possible to disentangle which absorption features might be associated to the same exocomet. Therefore, the comparison between the predicted and observed RV distribution is not straightforward, especially for the outer population. Due to the orbital alignment of stargrazers from the inner population, if a stargrazer was allowed to transit twice, it would likely add one more data-point to the narrow distribution and not change its shape. Depending on the orbital evolution of stargrazers from the outer system, allowing them to transit more than once could have a large and not necessary predictable effect on the shape of the distribution. Additionally, the simulation does not model the possibility of one parent body breaking up into a stream of particles on similar orbits, a possibility explored by [Beust et al. \(1996\)](#). This would again primarily affect the RV distribution of the outer population. In order to make a more meaningful comparison of the shape of the RV distribution of the outer population with observations, sublimation should be modeled. For a long time, exocomets were thought to not survive their close encounter with the star, and that this was the reason for their preferred red-shift. If a fraction of the outer population exocomets would indeed be destroyed, fully sublimated, upon close encounter with the star, this would skew the distribution of their RVs toward the red-shifted velocities. Including disappearance of exocomets due to sublimation would allow for a better comparison with the observations, but it would be highly model dependent. Due to the coherence of the orbits of the stargrazers from the inner population, their RV distribution is expected to be largely robust against these limitations.

The simulation performed in this study is a model of reality. It was set-up using measured system parameters, which come with uncertainties. Theoretical studies can only be as good as the observational data they rely on. For example, theoretical studies trying to explain the exocomet phenomenon of β Pic were published already ([Beust et al., 1991](#); [Levison et al., 1994](#); [Beust & Morbidelli, 1996, 2000](#)). They were performed before the discovery of the systems planets and therefore could not make accurate predictions. This study is also vulnerable against future discoveries. For example, the presence of an undetected planet outside of the orbit of β Pic b would likely make the outer system where one of the possible exocomet reservoirs predicted by this simulation is located dynamically unstable on short time-scales. The presence of such a planet has been theorized ([Matrà et al., 2019](#); [Lacquement et al., 2025](#)). Furthermore, if a terrestrial planet were to be located inside the orbit of β Pic c, it could disrupt the inner reservoir of exocomets predicted here. The fact that the simulation results of stargrazers from this population match well with the observed RV distribution suggests that the inner reservoir indeed exists. This way, the results of this thesis, and simulations by [Beust et al. \(2024\)](#), forbid the existence of a planet large enough to disrupt this region. Further studies of the inner stability region are required to quantify limits on the properties that a potential unseen planet in the inner system must have in order for the exocomet phenomenon to still be explained.

Other choices made in the set-up of the simulation are probably oversimplifications of reality. For example, the disk distribution was chosen to be uniform, meaning that the same amount of test-particles were seeded in the 1-2 AU bin as in the 29-30 AU bin. In reality that might not be accurate. Primordial planetesimal disks are likely more complex and could be approximated more accurately using a density distribution law. Such laws exist for the surface density of gas distributions in proto-planetary disks ([Lynden-Bell & Pringle, 1974](#); [Hayashi, 1981](#); [Desch, 2007](#)). A future study of the dynamical evolution of a planetesimal disk around β Pic could translate these laws into planetesimal densities to run more informed simulations. Note that this would also introduce a limitations, as this would still be a model, just a more informed and complex one. A particular consequence of the choice of the initial disk density distribution is the resulting magnitude of late stargrazers created from the two different regions in the system. An approximately equal amount of late stargrazers was produced from both the inner and outer regions, as reported in [Sect. 4.3](#), also see [Fig. 4.5](#). The simulation results should not be interpreted as though they predict that an equal amount of exocomets is expected to be created from both the inner and outer regions of the β Pic system as this result

is highly sensitive to the initial density of the simulated disk. The planetesimal density in the outer system is probably underestimated with respect to the inner region, as the test-particles were seeded uniformly in the semi-major axis, which is only one dimension. In two (and three) dimensions, the area of the 1-2 AU alias is smaller than the 29-30 AU alias, thus the density there is effectively smaller. Simultaneously it is also important to note that the late stargrazers created from the outer population arrive at highly inclined orbits and are therefore less likely to transit and be observed as exocomets compared to the stargrazers created from the inner region. In order to make statements about the relative rates of exocomets created from each region, the initial seeding of test-particles must be done in a more informed way. Better statistics of the inclinations of stargrazers are also needed, this likely requires simulations which produce a larger sample of late stargrazers.

Another example of a possible improvement to the simulation would be to in addition to the co-planar disk which was simulated here, also model the second observed disk-component which is inclined by $\sim 5^\circ$ with respect to the co-planar disk (Golimowski et al., 2006). The inclusion of a second component with a higher inclination with respect to edge-on orbit could result in more inclined late stargrazers. It would however likely not lead to more late stargrazers with small inclinations. Dynamical interactions with the planets seem to excite the orbits of planetesimals and increase their inclinations and eccentricities. A way of dampening the inclinations would be the inclusion of a gas-drag force. However, since β Pic is a secondary disk, it likely does not contain enough gas for it to be relevant. It was not chosen to be included in the simulation. A future study could test the effect of gas on the properties of stargazing particles, however that might be more relevant in systems with a primary proto-planetary disk, such as PDS 70 (Novais et al., 2025).

The analysis could be improved by inclusion of a larger number of test-particles, especially in the regions that generate late stargrazers. A larger sample of late stargrazers would allow for the investigation of details that are not revealed in the results here. The inclination statistics of the outer population is one example discussed above. Another example is investigating if the simulation predicts any differences in properties between the different stability regions included in the outer family. As can be seen in Fig. 4.1, the outer system features several stability regions between ~ 20 AU and ~ 28 AU. Late stargrazers are also being created from the gradual clearing of the outer stability region at ~ 30 AU, see Fig. 4.5. Currently, the statistics are shown for all of these groups bunched together as the "outer population" but a larger sample of particles in these regions could reveal if there are any differences in the stargrazers produced from the different sub-regions.

Finally, a potential future study could benefit from the use of a hybrid integrator which could allow for the inclusion of a larger number of test-particles. A new hybrid REBOUND integrator, TRACE, was released recently (Lu et al., 2024). It is designed to keep the accuracy of IAS15 during close encounters, while using a high-speed symplectic integrator otherwise. TRACE is in theory computationally inexpensive compared to IAS15 and would allow for the inclusion of a larger amount of test-particles for the same computational resources.

4.5 Sensitivity Tests

The first test of the sensitivity of the simulation results was performed testing how the results change as the planetary radii are changed. The reported values for the planetary radii are uncertain due to the fact that neither of the planets are transiting. Comparing the results of this smaller scale simulation with the same initial semi-major axis region of the global simulation showed that the number of collisions increases if the collision radii are increased, but since the number of collisions already constitutes less than 1% of all the different classifications, it did not change the branching ratios significantly, compare the left and right panels of Fig. 4.11. The largest changes to the branching ratio by doubling the planetary radii were that the number of collisions increased by approximately 70% and that the number of stable particles decreased by 11%, meaning that more particles which would have been stable instead collided with the planets as the radius increased. Importantly, the number of late stargrazers produced from this region decreased from 85 to 84 when doubling the radii of the planets, showing that the results and conclusions of this work are robust

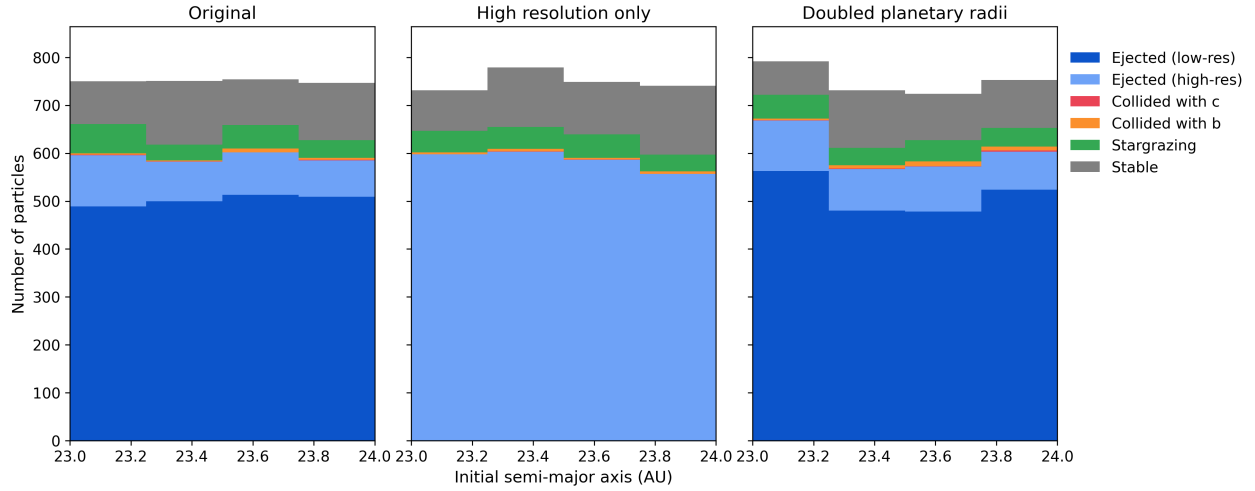


Figure 4.11: Resulting branching ratios of the sensitivity tests performed. **Left panel:** This figure shows the original result, corresponding to the 23-24 AU bin in Fig. 4.1. **Middle panel:** The result from a simulation that was done using only the high resolution time-step of 20 yr^{-1} . **Right panel:** The result from same region, from a simulation where the planetary radii were doubled.

against changes of the planetary radii.

A second test was performed over the same semi-major axis range, this time testing how the results would change if the time-step resolution was kept constant during the full duration of the simulation. The result of this test is shown in the middle panel of Fig. 4.11. The test showed that by simulating this bin of test-particles with the higher maximal time-step resolution, the total number of stargrazing particles decreased by 3% while the total number of particles classified as stable increased by 6%. These numbers are relative to the same semi-major axis range in the original simulation, set-up as described in Sect. 3.2, a zoom in of the original simulation results is shown in the leftmost panel of Fig. 4.11. Thus, by restricting the allowed maximal time-step that IAS15 can take, a small fraction of the stargrazing particles are instead stable on a time-scale of 25 Myr. In the original simulation, 85 late stargrazers were produced from this region. This number decreased to 75 in this test simulation. This test shows that the results are not sensitive to the switching of time-step resolution as this does not strongly affect the branching ratio, nor does it significantly decrease the number of late stargrazers produced from the region. The conclusion that the outer system, beyond the orbit of β Pic b, may be a possible origin of particles stargrazing at the age of the system is valid regardless of the choice of maximal time-step in the simulation ran in this study.

One of the important conclusions of this study is that exocomets from the outer population seem to be able to obtain large inclinations when stargrazing. The simulation results are highly dependent on the choice of initial conditions and the question arises if the resulting inclination distribution is an artifact of them. In order to test if the final inclination distribution of outer population exocomets is dependent on the initial inclinations of the test-particles, a criterion was imposed on the population. The outer population stargrazers were split up and only the test-particles which were initiated on inclinations smaller than 1° were included. In Fig. 4.12 the final inclinations of the whole outer exocomet population are shown again together with the inclination distribution of the limited sample. The two distributions have a similar shape and thus the results show no dependence on initial inclination. This means that the high inclinations obtained by some outer population exocomets are not only a product of the initial conditions, as such high final inclinations are obtained also by particles on initially very small inclinations. Therefore, if the simulation was repeated with a more narrow initial inclination distribution, it would not affect the final inclination distribution. The outcome that particles that evolve onto stargrazing orbits from the outer system obtain a wide spread of inclinations must thus be a general outcome of the dynamical evolution of the β Pic system.

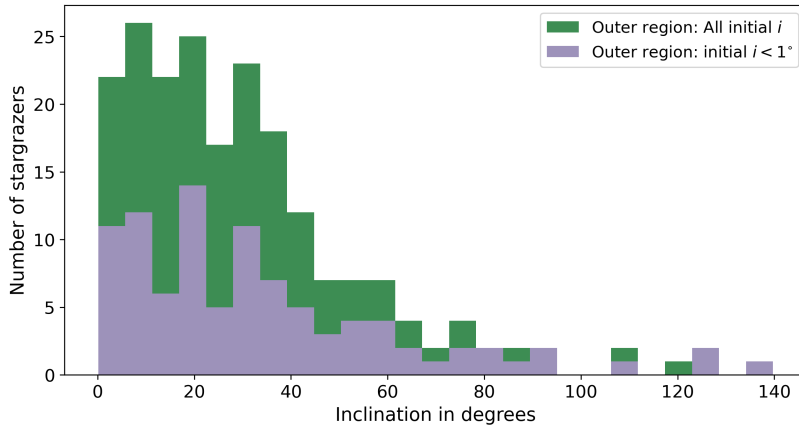


Figure 4.12: Inclinations of outer region exocomets. In green, all outer region stargazers are shown, regardless of their initial inclination. In purple, only the outer region stargazers which were initiated in the simulation on small inclinations of less than one degree, are shown. The final inclination distribution is independent of the initial inclination distribution of test-particles, as particles with initially smaller inclinations reach a comparable final inclination distribution as particles initiated with higher inclinations.

4.6 Modeling of Sublimated Material

A final aim of this thesis is to create models for the behavior of the gas released after sublimation from the exocometary surface. The models were constructed as described in Sect. 3.6, from which the β -factors and ionization time-scales were computed and compared with values found by previous studies. The results are presented and discussed in the sections below.

4.6.1 β -factor

The resulting β -factors for elements observed in β Pic exocomets are presented in Fig. 4.13 together with the results of Beust et al. (1989), Fernández et al. (2006) and Lehtmetts et al. (2026). For the sake of comparison, the β -factors presented in Fig. 4.13 were calculated using $R_{\text{star}} = 1.53 R_{\odot}$ and $M_{\text{star}} = 1.75 M_{\odot}$, following Lehtmetts et al. (2026). The results of this study seem to be in good agreement about the β -factors of most elements. Importantly, the best overlap is between the results of this study and the results presented by Fernández et al. (2006) who also use the PHOENIX library to generate the model flux. As can be seen in Fig. 4.13, the three literature results are not always in agreement with each other. For example, the β -ratio of SiII reported by Fernández et al. (2006) is larger than 0.5, while Lehtmetts et al. (2026) report a β -ratio significantly smaller than that, on the order of 10^{-2} .

The differences between the β -ratios found by the different studies can be explained by the different methods used. While the early study of Beust et al. (1989) uses a model flux which is an interpolation between two other stars, later studies by Fernández et al. (2006) and Lehtmetts et al. (2026) use advanced stellar models. Fernández et al. (2006) uses a model of high resolution which they broaden to account for the stellar rotation. Lehtmetts et al. (2026) use a low-resolution spectral model, meaning that the broadening due to stellar rotation does not have to be taken into account. In their paper, Lehtmetts et al. (2026) argue that the differences between their β -factors and the values found by Fernández et al. (2006) could be explained by the different flux models used. Since the methodology adapted by this thesis used the same, but updated, flux model as Fernández et al. (2006) it would explain why the results presented here are more similar to Fernández et al. (2006) than Lehtmetts et al. (2026).

The study of Beust et al. (1989) provides β -factors for three elements: Mg, Al and Ca. This study was performed just a couple of years after the first discovery of exocomets in β Pic and other elements were not

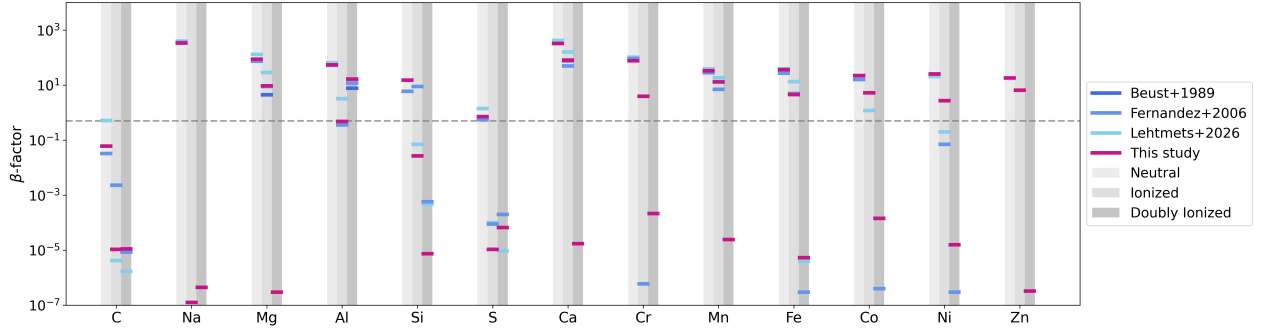


Figure 4.13: β -factors calculated for three ionization states of the 13 elements detected in β Pic exocomets. The results of this study are indicated in pink while the results of previous studies by Beust et al. (1989), Fernández et al. (2006) and Lehtmetts et al. (2026) are indicated in shades of blue. The dashed line indicates $\beta = 0.5$.

discovered in the exocomets yet. The later studies include a significantly larger amount of elements, however both Fernández et al. (2006) and Lehtmetts et al. (2026) were interested in investigating the properties of gas in debris disks, not exocomets specifically like Beust et al. (1989) and also the study performed for the purpose of this thesis. This work therefore includes β -ratios calculated for Zn, which has not been reported by the other studies.

For some ions, such as NaII, this study reports very small β -ratios while Fernández et al. (2006) reports $\beta = 0$ due to the fact that means that no ground state transitions are known in the range $1000 \text{ \AA} < \lambda < 50000 \text{ \AA}$ ($3e15 \text{ Hz} > \nu > 6e13 \text{ Hz}$). This is due to the fact that while Fernández et al. (2006) work with individual level transitions from the ground state, as in Eq. (2.16) while this study instead uses model opacities from DACE. These model opacities do not only include individual lines produced by transitions from the ground state, they include all known transitions and additionally a base-line continuum, see Fig. 3.4. Therefore, for elements which do not have any transitions in the frequency space covered by the model flux, the method implemented by this study still finds a non-zero β -factor arising from the continuum. The continuum is a numerical artifact and not physical (Grimm et al., 2021), thus the β -factor for NaII, NaIII, MgIII, CaIII, CrIII and MnIII should be interpreted as $\beta = 0$.

As can be seen from the left panel of Fig. 4.14, the β -factor calculation is limited by the frequency coverage of the PHOENIX flux model. The figure presents an example for NaI which has line transitions at low frequencies ($\nu \leq 6e13 \text{ Hz}$) which are outside of the frequency space covered by the flux model. Thus, the opacity is limited, and the β -factor is therefore likely larger than what is presented here. However, this difference is estimated to be small as the majority of the opacity of NaI, as well as the other elements, are within the limited frequency range. Furthermore, the flux is estimated to be very low at small IR frequencies, see Fig. 3.3 and can be estimated to not have a large peak at the missing frequencies. Therefore, even though the β -factors are likely underestimated by this thesis due to the limitation frequency limitation of the flux model used, other factors discussed below are likely affecting the resulting values more significantly.

An important caveat in the calculation of the β -factors for elements in the environment of β Pic is the calculation of the gravitational acceleration, g_{grav} , see Eq. (2.12). It uses the stellar parameters $R_{\odot}$ and $M_{\odot}$ and depending on different values chosen for these parameters, the resulting β -factors vary significantly. Just between the two solutions from T. 3.1, the mass of the star differs by almost $0.1 M_{\odot}$. The radius of β Pic was for the sake of the simulations performed in this thesis, see Sect. 3.2, chosen to be $1.8 R_{\odot}$ (Di Folco et al., 2004), while the value used by Lehtmetts et al. (2026) is $1.53 R_{\odot}$. In practice, the β -values reported should be interpreted as valid only for the specific set of stellar parameters used by a study as it is highly dependent on them. Importantly, depending on the actual parameters of the star, different elements will reach the 0.5β threshold and will not any longer be bound by the gravity of the star, however

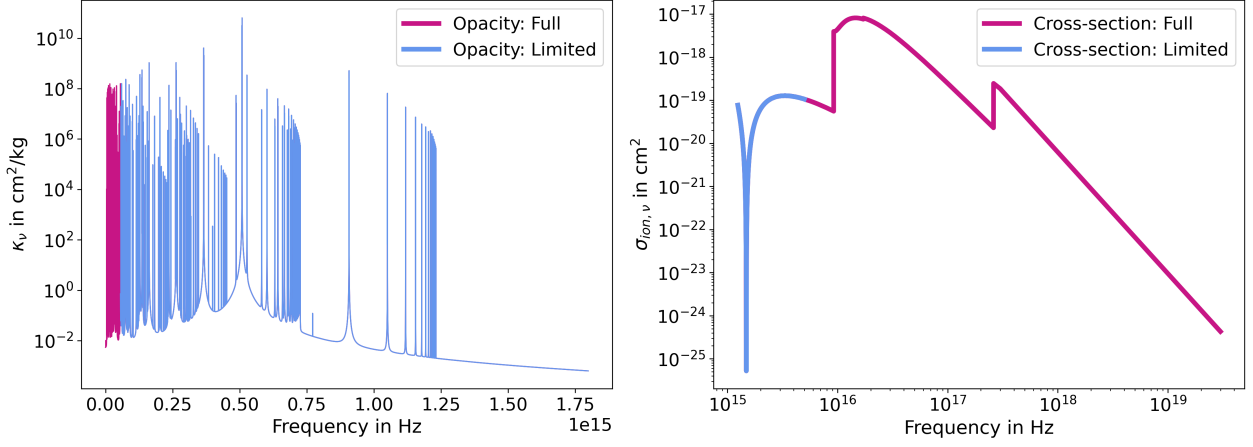


Figure 4.14: Models of κ_ν and $\sigma_{\text{ion},\nu}$ for NaI. **Left panel:** The opacity model used for the calculation of the β -factor for NaI. Over-plotted, in a darker color, is the frequency limited opacity model. A portion of the opacity model at low frequencies (IR-wavelengths) was not included in the calculations. **Right panel:** The model of the photoionization cross-section used for the calculation of the ionization time for NaI. Over-plotted, in a darker color, is the frequency limited cross-section model. A large portion of the cross-section model at high frequencies (UV-wavelengths) was not included in the calculations.

making a general statement is difficult due to the uncertainty of the stellar parameters. This is possible for certain elements which have a significantly large β -factor such as NaI, CaI and CaII which have a β -factor on the order of $10^1 - 10^2$. This value will get affected by the differences in stellar parameters however since it is significantly large, the conclusion won't change for these elements. This is also the case for elements with significantly small β -ratios such as carbon. [Fernández et al. \(2006\)](#) use observed photometric flux to calibrate their model instead of using the measured stellar radius, making their values not dependent on the uncertainty of the radius measurement, but on the uncertainty of the photometric observation instead.

It is therefore, for most elements, possible to make rough estimates about their behavior in the β Pic environment and to estimate their β -factors with an accuracy on the order of a magnitude. Due to the uncertainties present in the method, some of which are as basic as the unreliable measurements of stellar properties, it is not possible to constrain the β -factors with a high precision. However, for the purpose of this study, it is not necessary to do so. The purpose of this thesis was to understand the observational properties of β Pic exocomets and why they vary depending on what element the comets are observed in, especially regarding the recent detection of neutral sodium which is observable on a much more rarely than CaII ([Hoeijmakers et al., 2025](#)). The results show that NaI has an exceptionally high β -factor meaning that it is efficiently being blown away from the star. Since it is a neutral atom, it is not caught by the ionized cloud of gas surrounding the cometary nucleus and can therefore efficiently migrate away from the star, becoming more diffuse and lowering its probability of being observed. In comparison, CaII has a β -factor that is an order of magnitude lower than NaI and even if it is experiencing a large radiation induced acceleration, it is additionally being hindered from leaving the environment of the nucleus by breaking from the cloud of ionized gas around it. The β -factor of NaI is large, indicating that the atoms will be moved away from the vicinity of the star efficiently due to radiation pressure. The velocity boost, and therefore the distance the atom can away from the nucleus, is however limited by the time it takes for the atom to be ionized. This is discussed in the next section of this thesis.

4.6.2 Photoionization and Detectability of Elements

[Fig. 4.15](#) shows the resulting calculated photoionization rate Γ for two ionization states of the 13 elements detected in β Pic exocomets. The results are compared to the values reported by [Fernández et al. \(2006\)](#) and

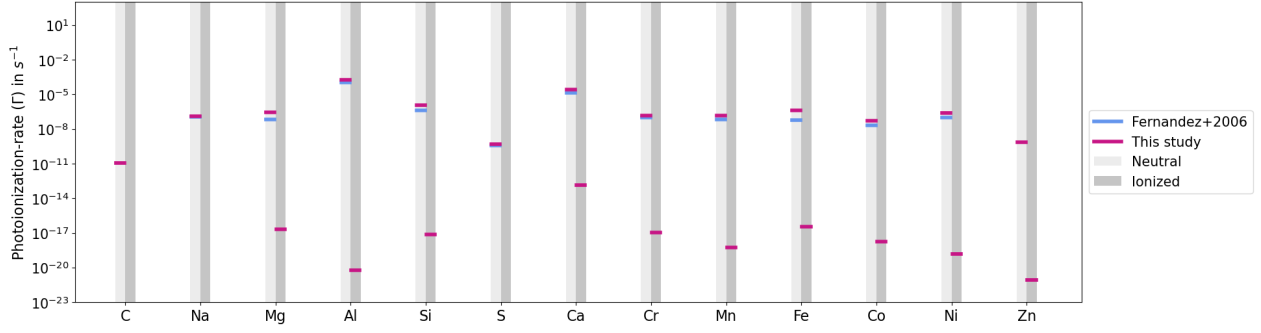


Figure 4.15: The photoionization rate Γ at a distance 100 AU from the β Pic star, found by this study in pink and by Fernández et al. (2006) in blue. The values are generally in agreement with each other. Note that this study also calculated Γ for singly ionized ions, while Fernández et al. (2006) only provide values for neutral atoms.

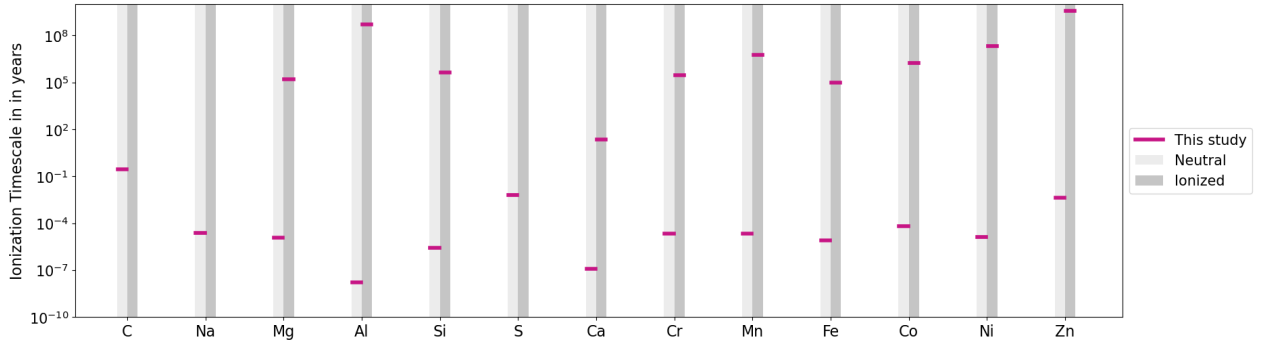


Figure 4.16: Photoionization time-scale t_{ion} , at a distance of 1 AU from the star, for elements detected in β Pic exocomets.

therefore the results are scaled to a distance of 100 AU to allow for this comparison. The results found by this study seem to agree well with the results reported by Fernández et al. (2006). The small differences could be attributed to differences in the updated PHOENIX models used by this study and the older models used by Fernández et al. (2006), as well as possible differences in models used for the photoionization cross-sections. This study uses data from the PhiDRATES database (Huebner & Carpenter, 1979; Huebner et al., 1992; Huebner & Mukherjee, 2015) while Fernández et al. (2006) use the CLOUDY C96.01 atomic data library (Ferland et al., 1998). Even though there are small differences that could have arisen from different models used by this study and Fernández et al. (2006), the results of the two studies are generally in agreement with each other. The study performed for the purpose of this thesis extended the methodology of Fernández et al. (2006) by additionally including ionization rates for singly ionized atoms. Doubly ionized atoms were not included as their cross-sections were not part of the PhiDRATES data-base. Note that some ions such as CII and NaII lack a photoionization rate estimate, as their cross-sections are fully outside of the flux model coverage.

The resulting ionization time-scales for the different elements are presented in Fig. 4.16. Note that the time-scales presented in this figure are calculated using a Γ evaluated at a distance of 1 AU from the star, in contrast to the Γ presented in Fig. 4.15 which were evaluated at 100 AU for the sake of comparison. The ionization time-scales in Fig. 4.16 therefore correspond to an average time before an atom becomes ionized by the stellar radiation at a distance where exocomets are expected to be found (Vrignaud & Lecavelier des Etangs, 2026), see Fig. 4.6. Generally, neutral atoms have a much shorter ionization time-scale than ionized atoms, as is expected due to the fact that the outer shell electrons are less tightly bound to the atom and

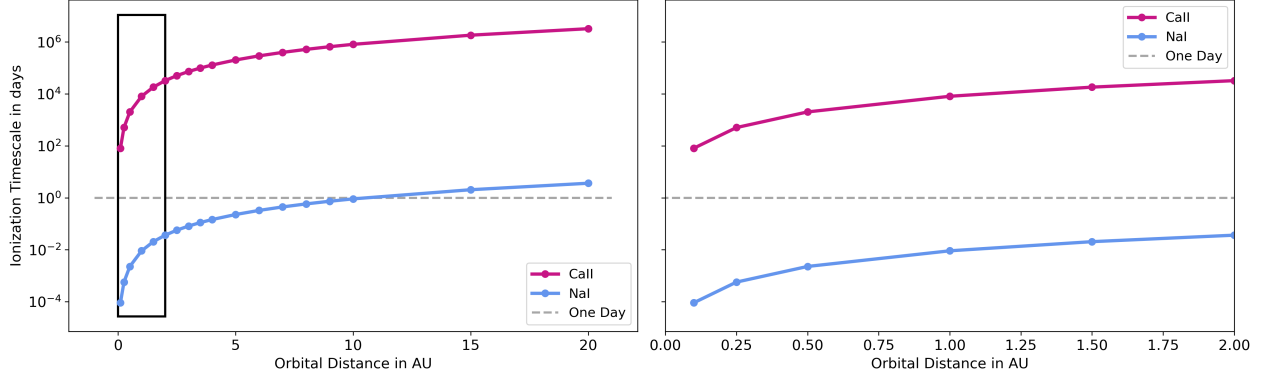


Figure 4.17: Ionization time, t_{ion} , for NaI and CaII as a function of distance from the β Pic star. Ionization time of one day (24 hours) is marked with a dashed line. The ionization time of NaI reaches one day at a distance of ~ 10 AU while the ionization time of CaII is orders of magnitude larger than that, even at small orbital distances.

are easier to remove by photons of lower energies. NaI has an average ionization time of around 13 minutes. The ionization time-scale of CaII is approximately 22 years, significantly longer, while for CaI it is only 4 seconds. This explains why CaI is not observed in the β Pic exocomets, as the calcium atoms are almost immediately ionized into CaII which has a long ionization time-scale. The short ionization time of NaI could also explain why it is observed so rarely in the exocomets of β Pic. The ionization time-scales of NaI and CaII are shown as a function of distance in Fig. 4.17. At low distances where exocomets are generally thought to be located, especially from the inner population or family D (Kiefer et al., 2014; Kennedy, 2018), the ionization time-scale of NaI is small. Therefore, this result could predict that NaI would be unobservable at these distances. The ionization time grows as the distance to the star increases. Exocomets located at larger distances could release sodium atoms which could remain in their neutral form for an average time of one day, at ~ 10 AU. At a distance of ~ 5 AU where exocometary gas has been observed to be transiting (Vrignaud & Lecavelier des Etangs, 2026), the ionization time is around 6 hours making it significantly more likely to be observed. The results of this thesis point toward the possibility that exocomets observed in NaI lines (Hoeijmakers et al., 2025) could be located at larger distances to the star and may be originating from the outer regions of the system.

Using the β -factors of the different elements together with the photoionization rates Γ , velocity boosts of the different ions was calculated. Note that this calculation was only done for neutral atoms, as the ions would be trapped in the vicinity of the cometary nucleus by the electric field created from the ionized cloud, and therefore their theoretical velocity boosts are not relevant. The velocity boost of all neutral elements can be found in Fig. 4.18. Elements which experience the largest velocity boost among the elements detected in β Pic exocomets are carbon, sodium, sulfur and zinc. Note that none of the investigated elements gain velocity boosts that are larger than the orbital velocity at 1 AU, which is on the order of 30 km/s, as discussed in Sect. 4.3.2. The material is expected to accelerate radially away from the star due to the acceleration induced by radiation pressure, however this acceleration is limited due to the low ionization time. The resulting maximal velocity the atoms gain on average is an order of magnitude lower than the orbital velocity at distances close to the star, where exocomets are expected to be located.

Finally, the expected size of the sodium cloud as calculated from the velocity boost of neutral sodium atoms and their average ionization time, is presented in Fig. 4.19. See Fig. 3.7 for a visualization of the approximated cloud geometry. At distances lower than ~ 18 AU the maximal sodium cloud would have a surface area that covers less than half of the stellar disk. At small orbital distances, shown in the zoom in (right panel) of Fig. 4.19, the area of the NaI cloud does not even reach 0.1% of the stellar disk. Here, 0.1% is assumed to be the spectroscopic detectability limit of a gaseous cloud. Hoeijmakers et al. (2025) find NaI exocometary features

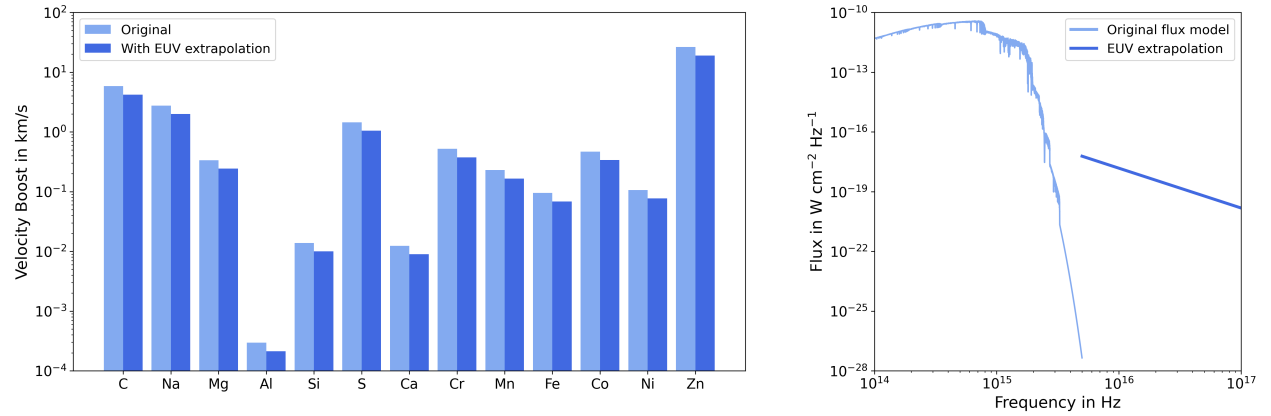


Figure 4.18: Right panel: Velocity boosts calculated for neutral elements observed in β Pic exocomets. The light colors indicate the velocity boosts calculated using the model flux spectrum, see Fig. 3.3. The darker bars show the results from the same calculation, but with an additional extrapolation of the flux to extreme ultraviolet light. **Left panel:** The original flux model, same as in Fig. 3.3, together with the EUV extrapolation.

that have the line depth of $\sim 0.9\%$, meaning that the cloud should cover up roughly the same fraction of the stellar disk, shallower lines have not been detected. From the results of this thesis, sodium is not predicted to be observable at short distances to the star due to its short ionization time. The cloud size becomes large enough to cross the inclusive detectability criterion at a distance just under 5 AU, which corresponds to one of the low-velocity exocomets observed by Vrignaud & Lecavelier des Etangs (2026). This seems to be the detectability distance limit for neutral sodium in β Pic exocomets, if no other processes are affecting the size of the NaI cloud.

Processes which are not taken into account here, but could increase the size of the NaI cloud into detectable levels are recombination of NaII ions and fragmentation of the cometary nucleus. If a significant fraction of the ionized sodium atoms were to recombine, neutral sodium would have an effectively longer lifetime, allowing for the cloud to grow larger, perhaps into detectable sizes. The electron density of the environment near the β Pic star should be high due to the vast amount of ionization of material released by exocomets. The rate at which the ion with charge i is re-created by recombination is given by $r = n_e n_{i+1} \alpha$, where n_e is the electron density of the environment, n_{i+1} is the density of an ion with charge $i + 1$ and α is the effective recombination coefficient (Pequignot et al., 1991). Assuming that the ionization state is steady, meaning that it is constant over time, as the number of ionized atoms is balanced by the number of recombination, so assuming ionization equilibrium, the fraction between the density of ion i and ion $i + 1$ can be estimated using $n_i/n_{i+1} = n_e \alpha / \Gamma$, where Γ is the ionization rate (Osterbrock & Ferland, 2006). Using the Γ calculated for NaI above, as well as an estimation of the recombination coefficient following Verner & Ferland (1996), the recombination rate of NaI was estimated as a function of time and can be found in Fig. 4.20. The critical electron density for which the density of neutral sodium dominates over ionized sodium is estimated to be on the order of 10^9 cm^{-3} . Electronic densities measured in β Pic exocomets are on the order of $10^5 - 10^7 \text{ cm}^{-3}$ (Mouillet & Lagrange, 1995; Vrignaud & Lecavelier des Etangs, 2024, 2026), however the ~ 5 AU comet observed by Vrignaud & Lecavelier des Etangs (2026) was found to have an electron density on the order of 10^3 cm^{-3} . This could mean that the electron density is generally not large enough for sodium to be visible, even though NaI could become observable for densities lower than the critical density. Neutral sodium could become observable in exceptionally electron dense exocomet clouds. Note that using the (Verner & Ferland, 1996) approach recombination coefficients can be estimated only for ions that are H, He, Li and Na-like, so not for CaII among others. A detailed investigation of the recombination rate of sodium as well as other species, is outside of the scope of this thesis, but it is a very interesting subject for a future study. It could for example be done by optimizing CLOUDY (Chatzikos et al., 2023; Gunasekera et al., 2023) for exocometary

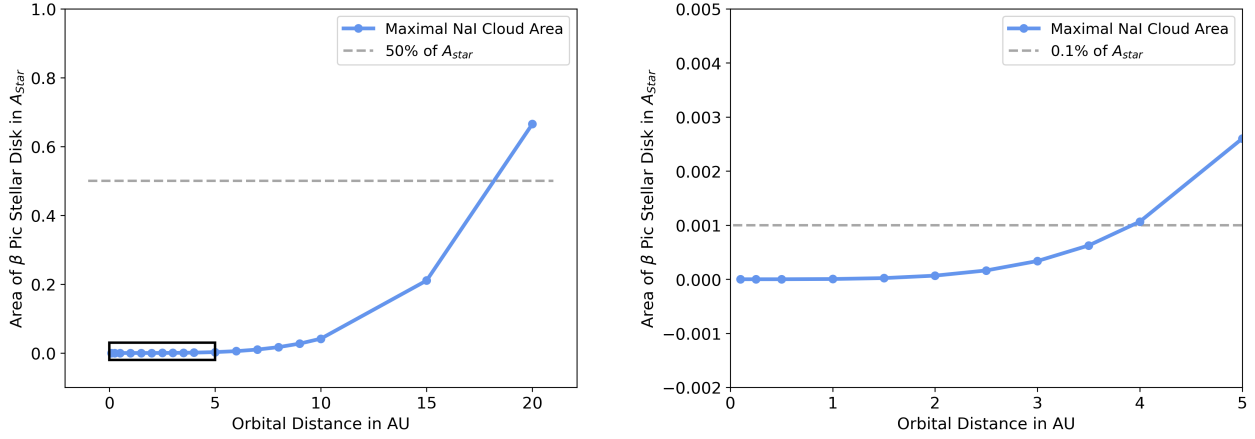


Figure 4.19: The projected surface area of the neutral sodium cloud released by an exocometary nucleus as a function of orbital distance. The dashed lines in the two panels indicate 50% and 0.1% of the stellar disk covered.

clouds. It would deepen the discussion about sodium detectability and could provide predictions for the likelihood of NaI observation, compared to CaII. This thesis provides a rough estimate meant to highlight the importance of a future exploration of this topic.

Another possibility is that if the nucleus of the comet were to fragment due to the close encounter with the star, it would cause the stellar disk to be obstructed to a higher degree by dusty particles released from the nucleus. These would then sublimate and release NaI, resulting in a larger surface area covered by the NaI cloud. In this scenario, the surface area of the CaII cloud would also increase, providing an explanation to why NaI is only detected in exocomets that also exhibit exceptionally deep CaII absorption features (Hoeijmakers et al., 2025). This scenario could be confirmed by simultaneous observations of spectroscopic NaI absorption and photometric observations of exocometary transits, indicating that a large amount of dust is produced at the same time that NaI is observed in β Pic exocomets. Note that more modeling of exocomet destruction is needed in order to make precise predictions, however there is evidence of such destruction seen from the change of acceleration direction of a CaII feature (Hoeijmakers et al., 2025).

Note that the area covered by the sodium cloud calculated here is only an estimation of the maximal area for an average cloud of NaI particles. Performing this methodology on CaII, which has a very large ionization time yields in a maximal cloud size that is several times as large as the star. This calculation provides a maximal area, assuming that the atoms can move radially away from the nucleus forming a sphere around it for the full duration of their average ionization time. This is not reasonable for CaII. The atoms are affected by radiation pressure, collisions and electromagnetic interactions with other ions, preventing the cloud from growing into these large dimensions. The observed exocometary CaII clouds have fill ratios smaller than 1 (Kiefer et al., 2014), meaning that they do not cover the full stellar disk. The cloud is likely observed not long after sublimation from the cometary surface and therefore has not had long to form a huge cloud. Note that the surface area of the cloud was computed assuming that the cloud is spherical, which is probably not the case. However, since this calculation only is meant to give a maximal surface area estimate, the spherical assumption is valid, especially for NaI which has a small ionization time. The cloud is likely diffuse and elongated, resulting in a smaller detectability for the same surface area. Note also that the velocity boost is expected to be directed in the radial direction, and the velocities in transverse and tangential directions are expected to be smaller. Therefore, the geometry used here, see Fig. 3.7 is likely an overestimation of the projected area of the gas cloud. This methodology also assumes that the full cloud is in front of the star, but parts of it could be outside of the stellar disk.

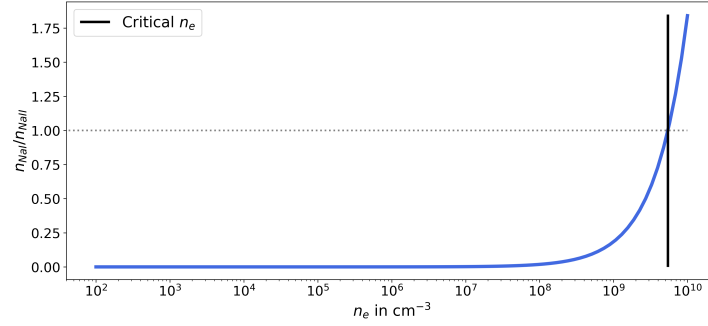


Figure 4.20: Ionization fraction of neutral and singly ionized sodium as a function of electron density. The critical density, where the neutral sodium starts to dominate over the ionized, is marked with a vertical line.

The cross-sections of several species have significant sizes in the UV, see Fig. 3.4, and could therefore be underestimated by the methodology. The model spectrum used for this project is calculated from a few parameters of the star to create the continuum, as well as a line-list of absorption lines. The model does not include additional effects that would change the flux output of a star at different frequencies. Importantly for this work, stars with convective envelopes emit ultraviolet (UV) photons from plasmas in their photosphere (Linsky, 2017). These are thought to be caused by magneto-hydrodynamic effects (Linsky et al., 2020) that are not taken into account in creating the flux model used here. Evidence of chromospheric activity has been observed in the far-UV in β Pic (Deleuil et al., 2001; Bouret et al., 2002), meaning that the star could output a higher UV flux than modeled. This could lead to the underestimation of both the β -factors and the photoionization rates, however the photoionization rates are more sensitive to this due to the cross-sections being high in the far UV for many species. The PHOENIX models are capable to account for non-LTE effects and emission form a potential chromosphere (Husser et al., 2013) however the non-LTE spectra are not accessible through the website, and StarRotator uses the LTE PHOENIX model spectra (Hoeijmakers et al., 2024).

The far UV modeling is therefore a large uncertainty to the calculation of the ionization rates and time-scales. As can be seen from the right figure of Fig. 4.14, the cross-sections of many elements are located far into the UV, on large frequencies which are not covered by the flux model. Fig. 4.14 shows an example for NaI, where the cross-section is largest at frequencies not covered by the frequency range of the flux model. The calculation is limited to only a small portion of the cross-section data and this could introduce a serious bias toward lower values of Γ and therefore larger ionization times, smaller velocity boosts and consequently smaller maximal size of the NaI gas cloud as presented in Fig. 4.19. In order to test the effect that this has on the results, a rough estimate of the extreme UV-flux of β Pic was made using data acquired by the Extreme Ultraviolet Explorer (EUVE; Bowyer & Malina 1991) which observed bright stars in the extreme UV, down to 100 Å. Craig et al. (1997) presented observations of Altair, a A7V type star with a mean temperature of 7594 K (Bouchaud et al., 2020) which is a star similar to β Pic. Since it is a cooler star, it would be expected to have more chromospheric activity, it can therefore be used as a rough upper limit for the EUV activity of β Pic. The EUV flux observed by Craig et al. (1997) is essentially zero, with a noise level of ~ 0.005 photons $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ and emission lines (see their Fig. 3). In order to determine if the noise level would be a large contribution to the flux model for β Pic used in this thesis, the noise level was re-scaled to the distance of the Altair star which is located 5.13 pc from the Earth (van Leeuwen, 2007) using distance modulus. Then, this level was extrapolated onto the EUV regime of the flux model and the calculations were repeated including this level. The noise level turned out to be significantly larger than the estimated UV flux, see left panel of Fig. 4.18 and including it into the calculations resulted in slightly lower velocity boosts. This difference does however not challenge the overall conclusion of this thesis, that neutral sodium clouds are generally too small to be observed at distances where at least one exocomet family is expected, unless other mechanisms like recombination and fragmentation increase the size of this cloud.

Chapter 5

Conclusions

This thesis has aimed to through theoretical simulations and modeling gain understanding about the exocomet phenomenon of β Pic. In order to form an understanding about the dynamical evolution of the system, a high precision N-body simulation was performed using the REBOUND IAS15 non-symplectic integrator (Rein & Liu, 2012; Rein & Spiegel, 2015). The simulation was set-up to model the β Pic star and the systems two planets, using recently measured stellar and planetary parameters (Lacour et al., 2021). Additionally, to model a primordial planetesimal disk, a disk of test-particles was included in the simulation. The fates of the test-particles were tracked over the the course of 25 Myr of evolution, longer than the estimated age of the system (Mamajek & Bell, 2014). Note that a portion of the work performed for the purpose of this thesis has been published in Jaworska & Hoeijmakers (2026). The conclusions presented here are an extension of the conclusions from this publication, including new findings.

The simulation showed that the system is highly dynamically unstable at orbital distances that lie in between the orbits of the systems two planets. Two main regions of dynamical stability on a time-scale corresponding to the age of the system were found: interior to the orbit of the innermost planet and exterior to the orbit of the outermost planet. Orbital distances larger than ~ 35 AU have yet not been affected by the gravitational influence of the planets, no particles initiated beyond this limit end up removed from the simulation. This simulation predicts that the cut-off of the β Pic dust disk would be located at this orbital distance, this is however not in agreement with observations that place this limit closer to 50 AU (Dent et al., 2014; Matrà et al., 2019) which could indicate the possibility of the existence of a third, unseen, planet in the system (Lacquement et al., 2025). The majority of all test-particles included in the simulation on semi-major axes smaller than 35 AU were found to be ejected from the system due to planet scattering. A small fraction of them collided with either one of the systems planets, while about one quarter ended up on stargrazing orbits, where their argument of periastron was smaller than the theoretical distance limit for observing exocomets, 0.4 AU (Beust et al., 1998).

An aim of this study was to constrain possible exocomet reservoirs, orbital distances in the system from where the exocomets which are observed today could be sourced. The results show that the two regions of dynamical stability produced stargrazers at times on the order of magnitude as the systems age, later than 10 Myr of simulation time. These particles are called *late stargrazers* in this work, and they model the exocomets observed in β Pic today. This thesis therefore finds that the β Pic system is highly dynamically unstable with the exception of two main regions of stability, the inner and the outer region, which are also shown to produce stargrazers at late times. Through N-body simulations, this thesis can point out two possible exocomet reservoirs in β Pic: an inner reservoir, located interior to 1.5 AU and an outer region, consisting of stability rings between 20 and 24 AU as well as the inner edge of the stability region exterior to 35 AU.

Upon further investigation of the late stargrazers produced by the simulation, this study can conclude that there are two distinct populations of stargrazers. Comets which originate in the inner region have orbits

that are well aligned with the orbit of β Pic c, indicating a structured eccentricity excitation due to resonant interactions with the planet. This result confirms the finding of the simulations performed by [Beust et al. \(2024\)](#) who show that exocomets can be produced from a region interior to the orbit of β Pic c by mean motion resonances with the planet. The inner region stargazers have a narrow and peaked distribution of radial velocities centered at 13 km/s with a standard deviation of 4 km/s. In contrast, stargazers from the outer region are on a more scattered distribution of orbits, indicating a more complex dynamical evolution. They also have a broader distribution of radial velocities. This result can be compared to observational findings reported by [Kiefer et al. \(2014\)](#) who identify two families of exocomets in β Pic, family S and family D. The RV distribution of family D match well with the inner population of stargazers produced by the simulation ran for the purpose of this thesis. Family S was found to have a broader RV distribution and could be compared to the outer population of stargazers, even though the shapes of the two distributions are not an exact match. The discrepancy in the distribution shape could be a result of the limitations of the simulation, such as the results being sensitive to the choices of initial conditions and classification boundaries. The limitations are discussed in detail [Sect. 4.4](#). The work performed for this thesis is the first theoretical study to predict two populations, or families, of exocomets in β Pic.

Even though this study predicts two possible dynamical populations of exocomets in β Pic, the inferred compositional properties of the predicted populations are in conflict with the interpretation of [Kiefer et al. \(2014\)](#) who argue that family D exocomets (narrow RV distribution) should be volatile rich while family S exocomets (broad RV distribution) should be devolatilized. The results of this thesis point to the opposite conclusion. The inner population exocomets (narrow RV distribution) must be primordially devolatilized, while the exocomets from the outer family (broad RV distribution) likely have retained a significant fraction of their volatile content during their migration from the outer reservoir to the vicinity of the star. Through these results, this thesis implies that a fraction of the exocomets observed in β Pic could be volatile rich. This thesis also makes predictions for observable differences of the two exocomet families, spectroscopical differences such as RV distributions but also photometrically observable differences such as transverse velocities.

Finally, with the aim to relate dynamical simulations and observations, a model of the dynamical properties of the gas sublimated by exocomets was constructed, as the observations probe the gas cloud and not the cometary nucleus itself. All 13 elements detected in β Pic exocomets ([Iglesias et al., 2025](#)) were included in this analysis. The results show NaI has a particularly large β -factor, meaning that it feels a large radiation pressure induced acceleration. Other ions such as CaII, MgI and MgII, as well as FeI and FeII have smaller β -ratios while still fulfilling $\beta > 0.5$ and thus being pushed radially away from the star due to the radiation pressure. Carbon has a $\beta < 0.5$, meaning that it remains bound due to the gravitational acceleration of the star and could act as a breaking agent, preventing other atoms from leaving the vicinity of the cometary nucleus, as proposed by [Fernández et al. \(2006\)](#). In this thesis, photoionization time-scales of the different atoms were calculated at 1 AU, a distance where exocomets are expected. The results show that CaI has a really low ionization time of a few seconds, while CaII ions generally survive for 22 years, explaining why CaI is never observed while CaII is the most common exocomet tracer. NaI was found to have an ionization time of around 13 minutes, possibly explaining why it is observed so rarely compared to CaII ([Hoeijmakers et al., 2025](#)). From the β -factor and photoionization rate, the average, maximal size of a NaI cloud was estimated, and this thesis suggests that NaI could be observable only if the cloud was located further than ~ 5 AU from the star, unless other mechanisms such as recombination and/or exocomet fragmentation could contribute to an increased cloud size.

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