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Anomalous Fe II Spectral Effects and High H I Lyα Temperature in Gas Blobs Near η Carinae

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Abstract—We consider the origin of the anomalously high intensity of the ultraviolet Fe II $\lambda\lambda$2507/2509 Å lines observed with high spatial and spectral resolutions from gas blobs (GBs) near η Carinae. This rare effect in stellar spectra is attributable to a combination of several factors: (1) the high hydrogen density ($>10^8$ cm^{-3}) that ensures the blocking of the Lyman continuum by GBs and, accordingly, the formation of a cold H I region with completely ionized Fe atoms; (2) the small distance between the GBs and the central star that ensures a high ($>$8000–10 000 K) Lyα H spectral temperature, which photoexcites Fe II selectively; and (3) the population of Fe II levels and, accordingly, the opening of a stimulated emission channel, which together with spontaneous transitions creates a radiative cycle where a single Fe II ion can multiply absorb Lyα emission. © *2004 MAIK "Nauka/Interperiodica"*.

Key words: *interstellar medium, gaseous nebulae, η Car, gas blobs, stimulated emission, Fe II.*

INTRODUCTION

The goal of this study is to interpret anomalous spectral effects, in particular, the UV 2507/2509 Å Fe II lines observed with high spatial and spectral resolutions from gas blobs (GBs) near η Carinae, the most massive and luminous star in the Galaxy. These UV Fe II lines are known to arise from the selective photoexcitation of Fe II ions by Lyα emission due to the chance coincidence of the wavelengths (Johansson and Jordan 1984; Johansson and Hamann 1993). Lyα H coincides with the transition that combines a low-lying (1 eV) excited state with two nearby high-lying Fe II states, while the spontaneous decay of these two states yields the above two spectral lines. These anomalously intense lines (2507/2509 Å) attract particular attention, because they are present in the spectra of GBs in the close vicinity of η Car taken with high spatial and spectral resolutions separately from the spectrum of the central star (see the review by Davidson and Humphreys 1997) using the Hubble Space Telescope (HST).

The first direct observations of compact GBs in the vicinity of η Car were made by using speckle interferometry (Weigelt and Ebersberger 1986). They revealed three GBs near the central star (at distances of several hundred AU from the central star). The sharply increased observational capabilities of the HST with a high-spectral-resolution spectrometer (the Space Telescope Imaging Spectrograph, STIS) made it possible to obtain spectra simultaneously with a high spatial resolution (0″.1) and a spectral resolution $\lambda/\Delta\lambda \simeq 10^5$ (Kimble *et al.* 1998). These instruments allowed the GB spectra to be observed separately from the photospheric radiation of the central star. Analysis of the spectra showed that the GBs emit many narrow lines of ionized elements (Zethson 2001). However, the extremely intense fluorescence Fe II $\lambda\lambda$2507/2509 Å lines (Davidson *et al.* 1995) and the most recent HST data (Gull *et al.* 2001) were most surprising.

THE FORMATION MODEL FOR THE Fe II $\lambda\lambda$2507/2509 Å LINES IN GBs

The column density of neutral hydrogen, $n_{\rm H} = N_{\rm H}D$, for GBs (in particular, GB "B") near η Car is estimated to be higher than 4×10^{21} cm^2, where $N_{\rm H}$ is the H I density and D is the GB size. This means that the GB is optically thick for the Lyman continuum ($\lambda < 912$ Å), i.e.,

$$\tau_{\rm c} = \sigma_{\rm ph}(\nu_{\rm c})N_{\rm H}D \gg 1, \qquad (1)$$

where $\sigma_{\rm ph}(\nu_{\rm c})$ is the photoionization absorption cross section near the ionization limit. Eq. (1) leads us to conclude that two spatially separated but adjacent regions are formed in the GB: a hot H II region to the side of the central star and a cold H I region

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behind it. These two regions are separated by the Strömgren boundary that passes inside the GB. The cold H I region is responsible for the numerous narrow Fe II lines that can be divided into categories: the fluorescence lines from high-lying levels photoexcited by Lyα and the forbidden lines from low-lying, metastable levels.

Condition (1) ensures the formation of a cold H I region where the Fe atoms are ionized by radiation with $\lambda > 912$ Å that passes through the H II region. This provides the basis for the physical model of the formation of the $\lambda\lambda 2507/2509$ Å lines (Johansson and Letokhov 2001; Klimov *et al.* 2002) in GBs at distances $R_\mathrm{b} \simeq (10^2 - 10^3) r_\mathrm{s}$ from the central star, where r_s is the radius of η Car. Another critical requirement is that the distance to the star R_b be small enough to ensure a high Lyα spectral temperature at the frequency of the Fe II absorption line.

The Lyα spectral temperature $T\alpha$ in the GB region can be estimated by two methods: (1) by estimating the energy of the radiation from η Car with $\lambda < \lambda_\mathrm{c}$ absorbed in the GB; and (2) by estimating the lower limit for $T\alpha$ from the condition for the formation of anomalously intense $\lambda\lambda 2507/2509$ Å lines. Let us consider both approaches.

ESTIMATING $T\alpha$, THE Lyα EFFECTIVE TEMPERATURE

Let us consider a spherical GB with a diameter $D \ll R_\mathrm{b}$ (Fig. 1). Condition (1) is satisfied if the hydrogen density N_H exceeds a critical value (Johansson and Letokhov 2001):

$$N_\mathrm{H}^\mathrm{cr} = \left(\frac{I_\mathrm{ph}}{\alpha_\mathrm{H}}\right)^{1/2} = \frac{r_\mathrm{s}}{2R_\mathrm{b}}\left(\frac{P(\nu_\mathrm{c}, T_\mathrm{s})\Delta\nu_\mathrm{ph}}{\alpha_\mathrm{H} D}\right)^{1/2}, \quad (2)$$

where α_H is the rate constant of the H II $\rightarrow$ H I recombination to the 2p state. The integrated intensity of the hydrogen-photoionizing stellar radiation with $\lambda < 912$ Å that reaches the GB surface is

$$I_\mathrm{ph} = \Omega \int\limits_{\nu_\mathrm{c}}^{\infty} P(\nu, T_\mathrm{s}) d\nu \simeq \Omega \mathbf{P}(\nu_\mathrm{c}, T_\mathrm{s})\Delta\nu_\mathrm{ph},$$

where $P(\nu, T_\mathrm{s})$ is the spectral Planck intensity distribution (in photons cm^{-2} s^{-1} sr^{-1} Hz^{-1}) for a star with a photospheric temperature T_s. For the estimation, we can use the effective frequency range $\Delta\nu_\mathrm{ph} \simeq 7$ eV above the ionization limit, where $P(\nu)$ and $\sigma_\mathrm{ph}(\nu)$ are large enough. At $T_\mathrm{s} = 30\,000$ K, $\mathbf{P}(\nu_\mathrm{c}, T_\mathrm{s})\Delta\nu_\mathrm{ph} \simeq 10^{23}$ photons cm^{-2} s^{-1}.

For $N > N_\mathrm{H}^\mathrm{cr}$, the neutral H I component of the GB absorbs almost all of the Lyman continuum radiation from the central star. The absorbed power is

$$P_\mathrm{abs}(\nu > \nu_\mathrm{c}) \simeq \Omega_0 S_\mathrm{abs} \int\limits_{\nu_\mathrm{c}}^{\infty} P(\nu, T_\mathrm{s}) d\nu \quad (3)$$
$$= \Omega \pi^2 D^2 \mathbf{P}(\nu_\mathrm{c}, T_\mathrm{s})\Delta\nu_\mathrm{ph},$$

where $\Omega_0 = 4\pi\Omega$ is the solid angle subtended by the GB from the central star and $S_\mathrm{abs} = (\pi/4)D^2$ is the area of the GB disk. The absorbed energy is reradiated in the hydrogen recombination spectrum, with the largest fraction ($\eta_1 = 0.7$) being emitted in the H I Lyα resonance line. The maximum optical density τ_0(Lyα) in the H II region at the center of the line is

$$\tau_0^\mathrm{m} = \sigma_0/\sigma_\mathrm{ph}(\nu_\mathrm{c}) \simeq 5 \times 10^3, \quad (4)$$

where $\sigma_0 = \sigma_{12}(\mathrm{Ly}\alpha) = 1.4 \times 10^{-14}$ cm^{-2} is the resonant scattering cross section at the center of the line, $\sigma_\mathrm{ph}(\nu_\mathrm{c}) = 3 \times 10^{-18}$ cm^2.

Lyα radiation is diffusively confined in the H II region, but the diffusive confinement time is limited by the fact that the number of scatterings is limited. This limitation is attributable to the Doppler frequency redistribution during the scattering of Lyα photons, which ensures relatively fast photon escape from the confinement region through the wings of the Doppler profile (Osterbrock 1989). Since the optical density τ_0 is limited by $\tau_0^\mathrm{m} = \sigma_0/\sigma_\mathrm{ph}$ and the damping factor for Lyα is $\alpha = \Delta\nu_\mathrm{rad}/\Delta\nu_\mathrm{D}$, the optical density in the Lorentz wings is $\alpha\tau_0^\mathrm{m} \simeq 1$. Therefore, Ly$\alpha$ photons escape from the H II region through diffusion with the Doppler width increasing by a factor of $\beta \simeq (\ln \tau_0^\mathrm{m})^{1/2} \simeq 3$. Thus, the total power emitted by the GB surface in the Lyα line is

$$P_\mathrm{em}(\mathrm{Ly}\alpha) \simeq 4\pi S_\mathrm{em} P(\nu_{\mathrm{Ly}\alpha}, T\alpha)(\Delta\nu_\mathrm{D}\beta), \quad (5)$$

where $T\alpha$ is the Lyα effective spectral temperature and $S_\mathrm{em} = \pi D^2$ is the area of the emitting surface of a spherical GB. In reality, S_em can differ slightly from πD^2 because of the peculiar shape of the emitting surface of the H II region (Fig. 1).

The mean Lyα spectral intensity at the GB surface is determined by the Planck distribution at frequency ν_α(Lyα) and by the spectral brightness temperature $T\alpha$, where the spectral broadening during the confinement is taken into account. In the steady state, assuming that the absorption of the confined Lyα radiation in the H II region of the GB is negligible, we obtain

$$\eta P_\mathrm{abs}(\nu > \nu_\mathrm{c}) = P_\mathrm{em}(\mathrm{Ly}\alpha). \quad (6)$$

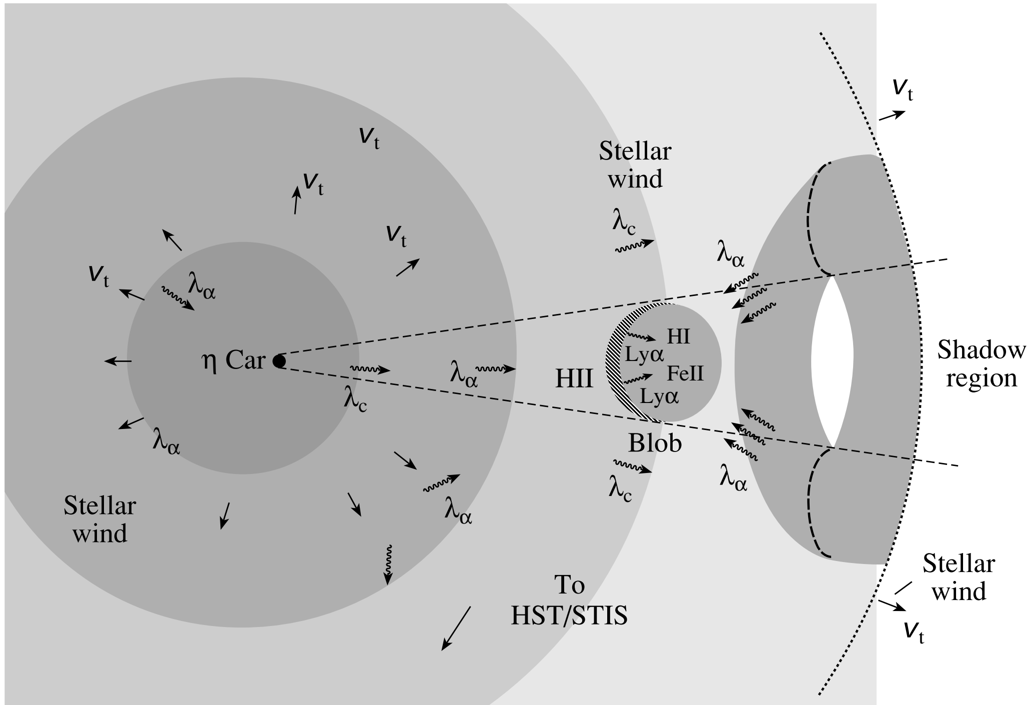

Fig. 1. The arrangement geometry of η Car and the gas blob (GB) that blocks the Lyman continuum radiation so that the front part of H II is completely ionized and the back part of H I contains Fe II ions. Fe II ions in the H I region are selectively photoexcited by Lyα photons that diffuse either from the H I region of the GB or from the nearby torus-shaped region of the stellar wind from η Car, which is also ionized by the Lyman continuum.

Hence, the brightness temperature $T\alpha$ for the Lyα radiation from the GB can be estimated from Eq. (6):

$$P(\nu_{\mathrm{Ly}\alpha}, T\alpha) = \frac{\eta_1}{4}\Omega\frac{\Delta\nu_{\mathrm{ph}}}{\Delta\nu_{\mathrm{D}}\beta}\mathbf{P}(\nu_{\mathrm{c}}, T_{\mathrm{s}}). \quad (7)$$

The dilution factor for the radiation from the central star is largely offset by the spectral compression of the absorbed Lyman-continuum energy into a relatively narrow recombination Lyα line. The compression factor f is

$$f = \frac{\Delta\nu_{\mathrm{abs}}}{\Delta\nu_{\mathrm{em}}} = \frac{\Delta\nu_{\mathrm{ph}}}{\Delta\nu_{\mathrm{D}}\beta} \simeq 10^3, \quad (8)$$

where $\Delta\nu_{\mathrm{abs}} \simeq \Delta\nu_{\mathrm{ph}}$ is the effective spectral width of the photoionization absorption, $\Delta\nu_{\mathrm{em}} = \beta\Delta\nu_{\mathrm{D}}$ is the width of the Lyα spectrum, and $\Delta\nu_{\mathrm{D}} = 6$ cm^{-1} is the Doppler width of the Lyα line.

For the closest vicinity of the central star, it is convenient to introduce a spectral brightness conversion parameter Ω_{br}:

$$\Omega_{\mathrm{br}} = \eta_1\Omega\left(\frac{\lambda_{\mathrm{Ly}\alpha}}{\lambda_{\mathrm{c}}}\right)^2\left(\frac{S_{\mathrm{abs}}}{S_{\mathrm{em}}}\right)f. \quad (9)$$

This parameter includes the absorbed energy conversion ratio η_1, the standard spatial dilution factor Ω, the mode density enhancement factor $(\lambda_{\mathrm{Ly}\alpha}/\lambda)^2$, the ratio of the absorption and emission areas, and the key spectral compression factor $f \gg 1$. The following equation relates the temperatures T_α and T_{s} (for $h\nu_{\mathrm{Ly}\alpha} \gg kT_{\mathrm{s}}, kT_\alpha$):

$$\frac{h\nu_{\mathrm{Ly}\alpha}}{kT\alpha} = -\ln\Omega_{\mathrm{br}} + \frac{h\nu_{\mathrm{c}}}{kT_{\mathrm{s}}}. \quad (10)$$

This relation is virtually equivalent to the expression for the source function in Lyα in terms of the source function in the Lyman continuum known for a nebula illuminated by a star (Sobolev 1975).

Note that the intensity of the Lyα radiation inside the H II region of the GB is higher that on the GB surface by a factor of δ that includes the diffusive confinement of the radiation:

$$\delta = \beta^2 = \ln\tau_0^{\mathrm{m}} \simeq 8\text{–}10. \quad (11)$$

According to the calculations by Auer (1968), the intensity of the Lyα radiation can be even a factor of 20 to 25 higher because of the confinement effect. Given this effect, the increase in Lyα intensity described by Eq. (10) can be written in a more accurate form:

$$\frac{h\nu_{\mathrm{Ly}\alpha}}{kT\alpha} = -\ln(\Omega_{\mathrm{br}}\delta) + \frac{h\nu_{\mathrm{c}}}{kT_{\mathrm{s}}}. \quad (12)$$

For the GB "B" of η Car, $\Omega_{\mathrm{br}}\delta \simeq 10^{-2}$, which corresponds to $T\alpha \simeq (10\text{–}15) \times 10^3$ K inside the GB.

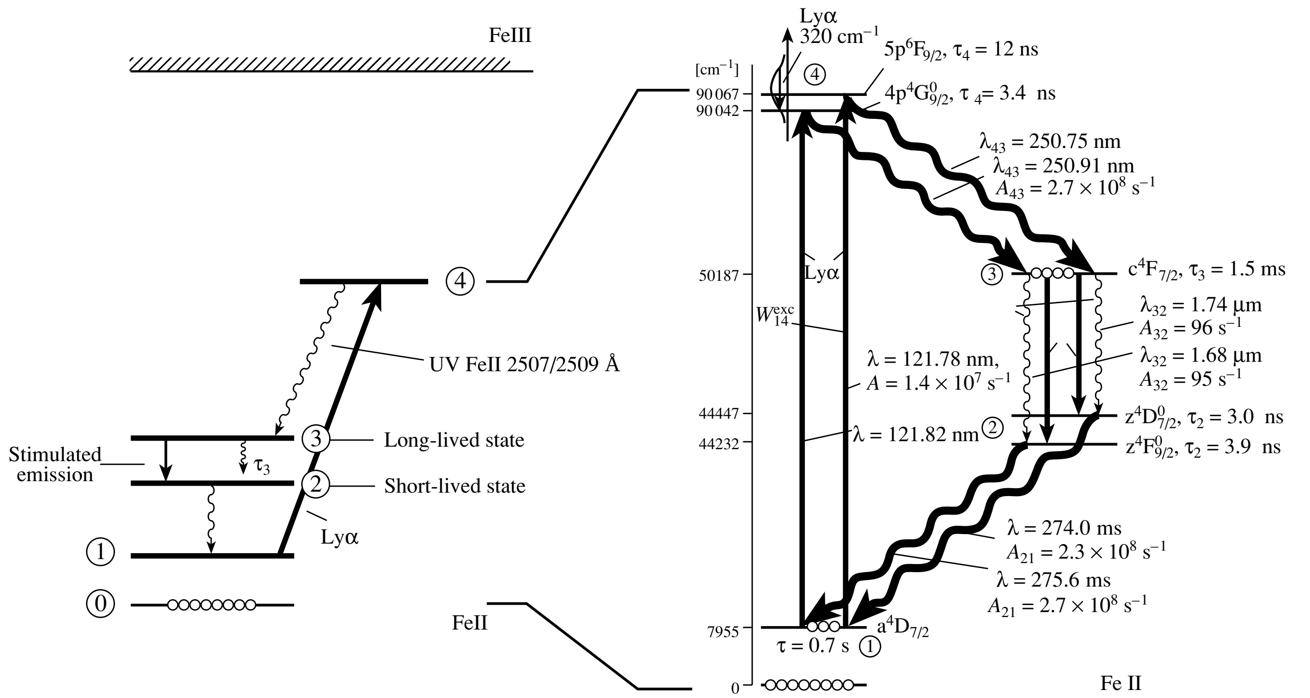

Fig. 2. Simplified and more detailed diagrams for Fe II quantum transitions, showing the quantum transitions of selective photoexcitation 1 → 4, rapid spontaneous decays 4 → 3, 2 → 1, and stimulated emission 3 → 2 that form a closed radiative cycle.

This value is comparable to or even higher than the electron temperature, implying a sharp change of the energy balance in the GB compared to a classical planetary nebula. Actually, the ratio μ of the Lyα radiation energy density inside the GB, $E(\text{Ly}\alpha)$, to the free energy density, E_{fr}, stored in charged particles (H II ions and electrons) becomes equal to

$$\mu = \frac{E(\text{Ly}\alpha)}{E_{\text{fr}}} = n_e\alpha_{\text{H}}\frac{D}{c}\delta\frac{\nu_{\text{Ly}\alpha}}{\nu_c}, \qquad (13)$$

where n_e is the electron density (or the density N_{H}, $N_{\text{H II}}$). This ratio has a simple physical meaning: the ratio of the lifetime of a Lyα photon inside the GB, $\tau_{\text{ph}} = \frac{D}{c}\delta$, due to the diffusive escape through the spectral line wings to the ion recombination time, $1/(n_e\alpha_{\text{H}})$. If we assume for the GB "B" of η Car that $n_e \simeq 2 \times 10^8$ cm^{-3} and $D = 10^{15}$ cm, then this ratio will be $\mu = 10$. The ratio of the density of $E(\text{Ly}\alpha)$ to the density of the charged-particle kinetic energy E_{kin} is even higher, because $h\nu_c \gg kT$. The density of the Lyα energy $E(\text{Ly}\alpha)$ is higher than the density of the Lyman continuum energy $E(\text{Ly}_c)$ at least by the factor of $\delta \simeq \ln\tau_0^{\text{m}}$ or even more (Auer 1968).Therefore, the following equation is valid for an optically thick (for Ly$_c$) GB:

$$E(\text{Ly}\alpha) \gg E(\text{Ly}_c), \quad E_{\text{fr}} \gg E_{\text{kin}}. \qquad (14)$$

This equation means that the photoprocesses in the GB are governed by Lyα and Lyman continuum, Ly$_c$, radiation. Such GBs may be called *radiation-rich* GBs, to distinguish them from standard *thermal* planetary nebulae (Aller 1984).

ESTIMATING $T\alpha$ FROM THE CONDITION OF THE Fe II RADIATIVE CYCLE

We can now independently estimate $T\alpha$ from the observations of intense Fe II $\lambda\lambda$2507/2509 Å spectral lines. Figure 2 shows a simplified diagram of the Fe II energy levels and quantum transitions related to the formation of these lines. The selective photoexcitation by Lyα radiation transfer Fe II ions from the low-lying metastable state 1 to the short-lived odd states 4 ($5p^6F^0_{9/2}$, $4p^4G^0_{9/2}$). These levels decay to state 3 (predominantly to $c^4F_{7/2}$ and, to a lesser extent, to $c^4F_{9/2}$), emitting intense $\lambda\lambda$2507/2509 Å lines. For $T(\text{Ly}\alpha) = T\alpha \gtrsim 12\,000$ K, the photoexcitation rate $W_{\text{exc}}(1 \to 4)$ exceeds the radiative decay rate for states 3:

$$W_{\text{exc}} = A_{41}\left[\exp\left(\frac{h\nu_{14}}{kT\alpha}\right) - 1\right]^{-1} \gtrsim \frac{1}{\tau_3} \simeq 10^3 \text{ s}^{-1}, \qquad (15)$$

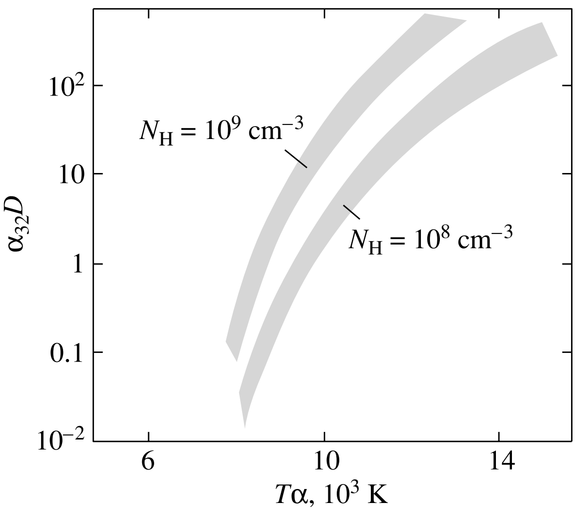

Fig. 3. Exponential $(\alpha_{32}D)$ in the amplification factor $K = \exp(\alpha_{32}D)$ versus effective (spectral) radiation temperature $T\alpha$ for two hydrogen densities N_H.

where $A_{41} = 1.4 \times 10^7$ s^{-1} is the Einstein coefficient for the $4 \to 1$ transition. Thus, if condition (15) is satisfied, then Fe^+ ions will be accumulated in the "pseudo-metastable" $c^4F_{9/2,7/2}$ states. The lifetimes of these levels are on the order of a millisecond, because they are associated with the truly metastable Fe II levels, but they lie above the next, higher configuration of opposite parity in the complex atomic structure (state 2 in Fig. 2). This accumulation of ions in pseudo-metastable states is unusual and is an important ingredient of our model for the origin of the anomalous $\lambda\lambda$2507/2509 Å lines. It should be emphasized that at densities $N_H \ll 10^{13}$ cm^{-3}, collisions give no contribution to the relaxation of the long-lived Fe II states.

Previously, it has been shown (Johansson and Letokhov 2003) that the accumulation of Fe II in the "pseudo-metastable" state 3 automatically leads to the population inversion of the ΔN_{32} levels with respect to the low-lying short-lived states 2 ($z^4D^0_{7/2}$ and $z^4F^0_{9/2}$). For a sufficiently large GB and high Fe II density, the arising amplification increases the intensity of the spontaneous radiation due to *stimulated* transitions whose rate is much higher than the spontaneous decay rate. Note that the inverse population of $\Delta N_{32} = N_3 - N_2$ emerges always, irrespective of $W_{\rm exc}$, because the lifetime of the lower level 2 is very short (3–4 ns). Under condition (15), the inverse population is at a maximum, whereas for $W_{\rm exc} \ll 1/\tau_3$, the amplification factor α_{32} for the $3 \to 2$ transition is given by

$$\alpha_{32} = \sigma_{32}\Delta N_{32}, \quad \text{where} \quad \Delta N_{32} = W_{14}^{\rm exc}\tau_3 N_3. \tag{16}$$

The stimulated radiation cross section for the $3 \to 2$ transition is $\sigma_{32} \simeq (1.2–3.7) \times 10^{-16}$ cm^2, and $N_1 = f_0 N_{\rm Fe}$ is the population density of the initial level 1, where f_0 is the fraction of the Fe^+ ions in state 1. Figure 3 shows a plot of the exponential $(\sigma_{32}D)$ in the amplification factor $K = \exp(\alpha_{32}D)$ for the $3 \to 2$ transition against the spectral temperature $T\alpha$, for two hydrogen densities N_H in the GB. We may take $D = 10^{15}$ cm and $f \simeq 10^{-2}$. The uncertainty in $(\alpha_{32}D)$ is attributable to the temperature uncertainty in the H I region, $T = 100–1000$ K, and the corresponding uncertainty in the Doppler width for the $3 \to 2$ transition, $\Delta\nu_D \simeq (200–600)$ MHz. As we see from (16), a decrease in N_3 for $W_{\rm exc} \ll 10^3$ s^{-1} at $T\alpha \leq 12\,000$ K may well be offset by an increase in Fe II density to achieve the required amplification factor. For example, at $T\alpha = 10\,000$ K, the excitation rate is $W_{\rm exc} = 10^2$ s^{-1}; to obtain a high amplification factor and, accordingly, the $1 \to 4 \to 3 \to 2 \to 1$ radiative cycle involving stimulated radiation, the population of the initial state N_1 should be increased by a factor of 10 by increasing the GB density and, accordingly, $N_{\rm Fe}$ by a factor of 10. This condition is milder than that in our previous paper (Johansson and Letokhov 2003). If, however, $T\alpha$ is lower than 8000–9000 K, a large decrease in amplification takes place, which is difficult to offset by increasing N_1. Therefore, an independent estimate of $T\alpha \gtrsim 10\,000$ K follows from the experimental observation of the intense Fe II $\lambda\lambda$2507/2509 Å lines that arise from cyclic transitions mentioned above.

CONCLUSIONS

In conclusion, let us discuss the Lyα radiation sources with the required temperature $T\alpha$ at the Fe II absorption wavelength in accordance with the geometry shown in Fig. 1. The required Lyα radiation can arrive from two regions: (1) the completely ionized front H II region of the GB, where intense Lyα radiation is generated through a photoionization–recombination cycle and (2) from the stellar-wind region of η Car adjacent to the back part of the GB that recedes from the GB with the terminal velocity v_t and, accordingly, has the required Doppler shift to compensate for the detuning between the Lyα and Fe II absorption wavelengths.

The first source is the H II region produced by the absorption of radiation from η Car in the region of the Lyman continuum, which is effectively converted into intense Lyα radiation (much more intense than the Lyα radiation from the central star).

This radiation from the H II region illuminates the immediately adjacent Fe II-containing H I region of the GB. This source has been discussed previously (Klimov *et al.* 2002). Doppler diffusion in the H I medium with a minimum optical depth $\tau_0(\mathrm{Ly}\,\alpha) \simeq 2 \times 10^8$ is required to compensate for the 2.4 Å detuning between the wavelengths of the Lyα line and the Fe II absorption line (Hamann *et al.* 1999). This value agrees with the previous estimate of the H I column density (Davidson and Humphreys 1997). At first glance, the H I region acts as a diffuse reflector of Lyα photons that escape from the H II region with open boundaries. This question was briefly discussed by Auer (1968), but we do not know any detailed calculations of the degree of diffusive penetration of Lyα radiation from the H II region into the H I region.

The second source is the torus-shaped zone of the stellar wind from η Car behind the GB (Fig. 1) that recedes from the GB with the negative Doppler shift sufficient to compensate for the wavelength detuning. This region of the stellar wind is illuminated by the Lyman continuum from the central star and emits Lyα. There are no accurate data on the hydrogen density in the asymmetric stellar wind from η Car near the GB, but, from the viewpoint of compensation for the frequency detuning and the maximum Lyα intensity, the location of the Strömgrem boundary in the stellar wind in the GB region would be optimal.

Further studies with the HST and the STIS camera can yield data on the contribution from each of the possible Lyα radiation sources to the selective photoexcitation of Fe II.

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