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## HEAVY ELEMENT ABUNDANCES IN LATE-B AND EARLY-A STARS. I. CO-ADDED *IUE* SPECTRA OF HgMn STARS

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### ABSTRACT

Very heavy elements (Pt, Au, Hg, Tl, and Bi) are found to be enhanced in the atmospheres of the chemically peculiar stars of the upper main sequence by up to a million times the solar system levels. Such enhancements are believed to result from atmospheric dynamics (i.e., diffusion) rather than scenarios that dredge up nuclear-processed material to the surface or transfer processed material between binary companions. However, the theoretical framework needs to be further constrained by observations beyond the realm of the spectral types for which such abundance enhancements are observed at optical wavelengths.

The *International Ultraviolet Explorer (IUE)* satellite collected spectra of bright stars for which chemical peculiarities have been derived from ground-based data. For several elements the abundance enhancements have only been recently measured using *Hubble Space Telescope* data and have therefore not yet been exploited in the *IUE* data. We have initiated a program to analyze *IUE* high-dispersion spectra to more fully characterize the pattern of very heavy element enhancement for many mercury-manganese (HgMn) stars and to potentially extend the spectral class (effective temperature) boundaries over which these abundance anomalies are known to exist. The abundances of very heavy elements in chemically normal B and A-type stars provide a base level that may be compared with the solar system abundances. These early spectral type stars may therefore reveal clues for galactic chemical evolution studies since they were formed at a later epoch than the Sun in the history of the Galaxy. This first paper presents the motivation for the analyses to follow, outlines our spectral co-addition technique for *IUE* spectra, and discusses the choice of model atmospheres and the synthetic spectrum procedures, while initiating the study by highlighting the abundance of gold in several HgMn stars.

*Subject headings:* stars: abundances — stars: chemically peculiar — ultraviolet: stars

### 1. INTRODUCTION

The abundances of the chemical elements, as derived from study of stellar photospheres, have their origins in processes related to the chemical composition of the star-forming cloud, the residue of nuclear processing from within the stellar core that is dredged up to the photosphere, and physical processes within the stellar photosphere/envelope that may preferentially segregate ions or isotopes of particular elements. The first two processes have led to our understanding of chemically normal, or solar-composition, stars, while the third is considered to be responsible for creating “peculiar” spectra. Through the cyclical star-formation and evolution scenario over many stellar generations, the interstellar medium (ISM) and later generations of stars become enriched in heavier elements. As telescopes and their instrumentation become more able to identify and study individual stars in nearby galaxies, the work performed on stars in the vicinity of the Sun provides the foundation for understanding the chemical and dynamical evolution of Local Group galaxies.

While the tools and techniques for galactic chemical evolution (GCE) studies are being further developed, efforts must

also be concentrated on understanding physical processes best studied via stars in the immediate vicinity of the Sun. Their close proximity allows them to be studied over a wide wavelength domain and at sufficiently high spectral resolution to sort out the effects of various physical processes upon the observed spectrum. In general, one may expect the hotter stars to provide a less confusing sample of heavy element chemical enrichment of the ISM over cooler stars, for which the slower pace of stellar evolution will lead to a wide spread in the observed abundances in large stellar samples.

In principle the atmospheres of late-B and early-A main-sequence band stars should be the simplest ones to model and understand. Convection is apparently absent, and stellar winds are very weak. Many appear to have little or no photospheric microturbulence. However, this very stability permits diffusive separation to occur and in approximately one-quarter of the B and A type stars spectral anomalies to appear as seen through their effects upon spectral line strengths, interpreted as elemental abundance enhancements or deficiencies relative to solar system material, and in line shapes indicative of deviations from the solar system isotope mixture.

The anomalies of the heaviest elements remain extremely mysterious. In the HgMn class of chemically peculiar (CP) late-B stars, several of the heaviest elements (Pt, Au, Hg, Tl, Bi) can be overabundant relative to solar system material by as much as 5 orders of magnitude (see the review by Smith 1996a). However, many otherwise “normal” late-B and early-A stars may show overabundances of at least some of these very heavy elements. Smith (1997) for example, found from *International Ultraviolet Explorer (IUE)* satellite high-dispersion observations that some normal, late-B stars showed mercury abundances that were enhanced by 1.5 to 2 orders of magnitude.

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Sadakane (1991) suggested from *Copernicus* data that lead in Sirius is enhanced by 3 orders of magnitude, while Faraggiana (1989) reported a possible detection, and hence assumption of enrichment, of Pb II  $\lambda$ 2203 in other Am stars.

A comprehensive understanding of the optical region has been formulated from the efforts of many researchers. However, the optical investigations for hot stars suffer from a paucity of heavy element lines. For many heavy elements there are few or no observable lines. In the ultraviolet, where most singly ionized and some doubly ionized ions have their resonance lines, this situation is dramatically improved. Analysis of *IUE* spectra has allowed abundance determinations for several important elements (Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, and Hg) in a number of peculiar and normal stars (Adelman et al. 1993a, 1993b; Smith 1993, 1994, 1996b, 1997; Smith & Dworetzky 1993).

Unfortunately, the results from *IUE* data are constrained by their limited signal-to-noise ratio (S/N) (seldom more than 40:1 even for the very best co-added data) and limited resolution ( $\lambda/\delta\lambda \approx 12000$ ). For a small number of CP stars, observations made with the *Hubble Space Telescope's* Goddard High Resolution Spectrograph (*HST* GHRS) and the Space Telescope Imaging Spectrograph (*HST* STIS) are also available. These have much higher resolution ( $\lambda/\delta\lambda$  up to 92,000) and S/N ranging up to 110:1. These high-quality data allow intrinsic stellar spectra to be viewed with unprecedented detail and the direct determination of the strength and location of individual lines that in *IUE* spectra are seen only as unresolved blends. Wahlgren et al. (1993) demonstrated how the use of the high spectral resolution GHRS data could improve abundance determinations from *IUE* data. By using GHRS observations of select lines of platinum, gold, and mercury in  $\chi$  Lup and  $\kappa$  Cnc, they determined abundances from *IUE* high-dispersion spectra for a small sample of stars. More recently, Wahlgren & Evans (1998) found the abundances of very heavy elements in the HgMn companion to the Cepheid SU Cyg. Their work applied the same synthetic spectrum techniques and atomic line data of *HST* GHRS analyses to extract abundances of platinum, gold, mercury, and thallium from *IUE* high-dispersion spectra.

The star most extensively studied with the GHRS has been  $\chi$  Lup (B9.5 IV HgMn + A2 Vm) (Leckrone et al. 1999), whose elemental abundances have been determined for a large fraction of the periodic table. Abundance enhancements for most elements through the iron group are modest, and indeed, among these elements, underabundances are more common than are overabundances. The heaviest elements exhibit the largest departures from the solar system pattern, with platinum, gold, mercury, and thallium showing the most extreme overabundances. Each element has at least one strong line (Pt II  $\lambda$ 2144, Au II  $\lambda$ 1740, Hg II  $\lambda$ 1942, Tl II  $\lambda$ 1321, and Bi II  $\lambda$ 1436) that has measurable effects on *IUE* high-dispersion spectra for the abundances found in HgMn stars. But only for mercury has a comprehensive analysis been performed for a substantial number of stars (Smith 1997).

The abundances of the very heavy elements present a wealth of information that can be applied to understanding the nature of the warm chemically peculiar (CP) stars and to constraining theories forwarded to explain observed spectrum anomalies. In addition, a possible general enhancement of heavy elements in normal late-B type stars that may be attributed to a general enrichment of the ISM through stellar and galactic evolution can be explored. The use of results obtained from spectral analyses performed at a significantly higher spectral resolution than that afforded by the *IUE* satellite has yet to be used in

conjunction with the *IUE's* vast archival resources. We intend to make such an application to obtain insights of a fundamental nature for both CP stars and GCE, as well as to subsequently pose new, directed questions for future research efforts that would require the capabilities of modern telescopes and instrumentation.

## 2. PROGRAM SCIENCE DIRECTIVES

The determination of abundances for the very heavy elements, for both normal and peculiar stars within the spectral type range mid-B to mid-A is vital to two independent fields of study: the nature of CP stars and galactic chemical evolution. Several classes of CP stars coexist within this spectral range. While they are conventionally divided into the magnetic (Bp and Ap) and nonmagnetic (HgMn and Am) subclasses, this distinction may indeed be archaic as studies of the supposed, nonmagnetic HgMn stars might reveal the vestiges of weak or unstructured fields (Hubrig et al. 1999) and common abundance enhancements across classification boundaries (Wahlgren & Dolk 1998). Other discriminating characteristics among these groups include certain elements that are found to show anomalous spectral line strengths and shapes. Our study does not attempt to isolate the groups from each other by identifying discriminants, but rather to understand observed differences in existing groups and to try to find common physical processes that may clarify the observed distinctions. For example, the distinction between HgMn and Am stars is likely to result from a physical process (perhaps diffusion) manifesting itself differently as the effective temperature is varied.

The connection between the separate classes of CP stars has been taken up by few investigators, as for example Adelman et al. (2003), Dolk (2002), and Wahlgren & Dolk (1998). The latter two studies are based on optical region and few *IUE* high-dispersion spectra of hot-Am stars. Their analysis of the Hg I  $\lambda$ 4358 and Hg II  $\lambda$ 1942 and  $\lambda$ 3984 transitions finds that although the hottest Am stars do not show evidence for Hg I and Hg II at optical wavelengths, many show enhanced Hg II  $\lambda$ 1942 at a level of factors of 10 to 100 above solar material. (The greater intrinsic strength of the Hg II  $\lambda$ 1942 transition makes it more sensitive to the presence of Hg II than  $\lambda$ 3984.) The reduced level of the mercury enhancement, relative to the somewhat hotter HgMn stars, is perhaps consistent with diffusion theory since the atmospheres of A stars begin to experience mixing through the onset of convective motions, which would destroy the stability required to foster diffusive separation of the isotopes. Another candidate might be a relative ineffectiveness of diffusion at the lower effective temperatures.

Our present undertaking into abundances of very heavy elements attempts to characterize anomalies that span CP star boundaries and provide the constraints that are needed by theorists in their quest to model these anomalies. The current theoretical paradigm for the HgMn, and to some extent the Am, phenomenon is diffusive segregation of ionic and isotopic species as a result of a balance of radiative and gravitational forces within the atmosphere and subatmospheric levels of warm stars. The atmospheric structure for stars in the effective temperature range 10,000–16,000 K allows helium to settle to subphotospheric levels. Such a deficiency of helium is observed in HgMn stars. Heavy elements, such as Pt and Hg, are thought to be subsequently levitated upward in the atmosphere by momentum transfer through line absorption provided that strong transitions of the ion are located in the spectral region of essentially maximum flux levels. An additional criterion is that

the atmosphere be free of the mixing effects of turbulence that can arise through rapid rotation, which would act to destroy any isotopic or ionic separation that may occur. In extreme cases theory predicts that the lighter isotopes may be forced out of the atmosphere altogether. Observations conducted with the *HST* GHRS of strong lines of Pt and Hg show line profiles that indicate non-solar system isotopic mixtures (Kalus et al. 1998; Leckrone et al. 1998; Proffitt et al. 1999); however, the mixtures observed for different ionization states do not prove the tenants of simple diffusion theory. The influences of other important atmospheric processes (i.e., magnetic fields, convective motions, stellar winds, and mass loss) are also yet to be understood but are considered to be contributing factors to the formulation of the observed spectral features.

While the *IUE* high-dispersion spectra will not be able to provide insights into isotopic composition (owing to an insufficient spectral resolution), they will allow us to address rather fundamental issues about CP stars:

1. Are the abundances of very heavy elements related to effective temperature or stellar age? Revisions in the calibrations of  $T_{\text{eff}}$  and  $\log g$  based upon *Hipparcos* parallax data provide more accurate placement of the CP stars in the H-R diagram. We will therefore be better able to identify abundance anomalies as a function of age, if they exist.

2. Is the pattern of the elemental abundance distribution in all HgMn stars similar to those observed in the stars  $\chi$  Lup and HR 7775? Both stars display tremendous enhancements of Pt, Au, Hg, and Tl, with HR 7775 showing a much stronger Bi enhancement than  $\chi$  Lup. All other very heavy elements have essentially solar-like abundance levels. Is this pattern maintained in other CP stars? If so, what does this tell us about the nature of the stellar atmosphere? It is for only these two stars (and SU Cyg B) that an abundance of Tl has been determined, as there are no strong Tl II lines at optical wavelengths.

3. Does the physical process responsible for chemical anomalies cross the assumed boundaries of the CP star classes, or are these classes physically distinct? We will be able to test this by determining whether there are continuous or discrete variations in abundance anomalies with temperature.

4. Does a strong dipole or higher order magnetic field help to support the heavy elements? We will test this by comparisons of magnetic and nonmagnetic stars of similar spectral type, and as a function of magnetic field strength.

### 3. DATA SELECTION AND REDUCTION

#### 3.1. Target Selection

The *IUE* archives contain the spectra of approximately 200 stars in the mid-B to mid-A spectral range. However, not all of these spectra are suitable to our study. Some stars are spectroscopic binaries with the secondary spectrum contributing to the region(s) of interest. Other stars rotate rapidly enough to further add to line blending complications that already exist. We have culled the archives to eliminate those targets and exposures for which binarity, line blending through high rotation (typically for  $v \sin i$  greater than  $30 \text{ km s}^{-1}$ , and data quality (insufficient S/N, cosmic rays, and bad pixels) are a problem.

An additional concern of target selection is the target classification. Placement of stellar spectra into one of the *IUE* object class designations followed the recommendation of the observer. When considering chemically peculiar stars it is not uncommon to find the spectral images of hotter Am stars classified as nonpeculiar, such as for the star Sirius. Over 200

high-dispersion spectral images exist for stars classified as Am stars in the *IUE* archives, and approximately 450 images for the Short Wavelength Prime (SWP) camera alone for normal early-A stars. Therefore, we searched through both normal and peculiar star categories for the late-B and early-A stars for stars of any given classification and applied our collective experience in the field.

#### 3.2. Data Extraction

After having identified suitable targets, their spectra as reprocessed by NEWSIPS were obtained from the *IUE* data archives using the Space Telescope Science Institute data archive system MAST.<sup>6</sup> We checked their quality in the spectral regions identified as important for our study by initially examining the plots available on the MAST Web site. In a few cases the archives possess multiple observations of the same target, which were obtained expressly for co-addition to improve the S/N characteristics using a technique that was developed by Leckrone & Adelman (1989). These data sets are largely limited to the late-B type stars of the HgMn class, although such data also exists for a few early A-type stars (for example,  $\alpha$  Peg,  $\theta$  Leo, and  $\gamma$  Gem). Prior to co-addition, we scrutinized occurrences of multiple images for binary stars for phase(s) in which contamination of the lines of interest would pose problems for the analysis owing to spectrum variability. When identified, these images were not included.

#### 3.3. Spectrum Co-Addition

First, the fluxes are normalized by assuming that the median flux or count rate of all data points in each exposure of the same star for a given camera should be the same. Fortunately, saturated or extrapolated values in *IUE* data are usually assigned flux values that are greater than their true values. Thus, as long as fewer than half the points in each spectrum are bad, the median value should not change. Our procedure lacks provision for varying the normalization as a function of wavelength except by co-adding separate wavelength intervals. For spectra with large numbers of spectra (greater than 20), it was usual to divide the wavelength range in several parts. All spectra are scaled so that their median fluxes are the same as that of the brightest one. We also divided the wavelength region of a given camera for each star so that we could exclude spectra that were grossly overexposed in a particular region and still use them in properly exposed regions.

Next, the wavelength scales are aligned. The cross correlation is done by a routine known as newshift, a heavily modified version of the hrs\_shift routine. The hrs\_shift routine shifted the spectra to find the offset where the sum of the squares of the differences at each point was at a minimum. This procedure required that the subarrays to be cross correlated have good data points in each and every exposure and that the same number of data points be compared at each potential shift. This made it difficult to handle data with randomly placed bad data points. The new routine finds the shift that minimizes the reduced  $\chi^2$  of the difference between the spectra sum  $[(f_1^2 - f_2^2)/(s_1^2 + s_2^2)]/(n - 1)$ , where  $f_1$  and  $f_2$  are the fluxes,  $s_1$  and  $s_2$  are the error vectors, and for each shift the sum is taken only over those  $n$  points where the good data points in each spectrum align for that shift. The actual number of points,  $n$ , used to compute the cross correlation function will differ for each shift. But since we normalize the sum by the number of points used,

<sup>6</sup> See <http://archive.stsci.edu>.

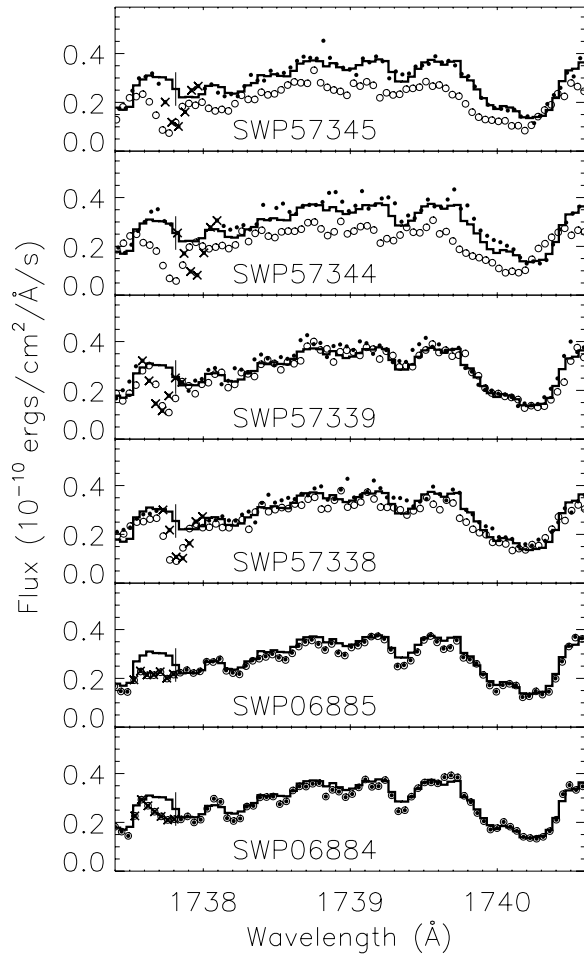


FIG. 1.—Individual component spectra vs. co-add spectrum. Corrections to the individual spectra in the co-add process are exemplified by six SWP spectra of the chemically peculiar star HR 7775. The individual spectra are presented in separate panels. The plotted data include the uncorrected mxhi data points (*open circles*) and the result of administering shifts in wavelength and flux (*solid dots*) prior to co-addition (*histogram*). Also noted are pixels flagged as being bad (*crosses*) in the mxhi file and the location of a single pixel of the co-add that possesses an interpolated flux value.

the minimum of the above function still usually finds the best alignment even when a substantial fraction of each spectrum is excluded from the sum. As for *hrs\_shift*, the final shift is determined to subpixel accuracy by quadratic interpolation of the cross correlation function in the vicinity of the minimum.

In practice we select one spectrum as the wavelength reference and the other spectra are shifted individually to align with this one. A separate cross correlation is performed for the short- and long-wavelength halves of each spectrum and the wavelength scales of each spectrum are corrected assuming there is a linear relation between the two wavelength scales, thus both a shift and a change in dispersion are allowed. Points that are flagged as bad in any way in the *IUE* spectra, including those listed as having an extrapolated ITF, are excluded from both the wavelength cross correlation and the final co-addition.

Wavelength bins are defined with a spacing approximately equal to that of the reference *IUE* spectrum's wavelength scale, except for a constant  $\Delta\lambda/\lambda$ . Each bin is assigned a flux value equal to the weighted mean flux value (weighted by the error vector) of all good data points that fall into the bin's wavelength range. Each bin's wavelength is based on the average of the wavelengths of the good data points that fell into that bin.

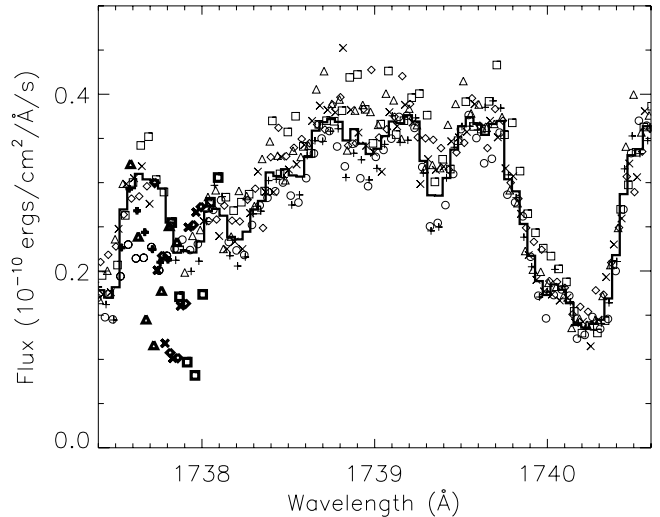


FIG. 2.—Scatter within individual component spectra. The spectra from the previous figure are overplotted together on the resultant co-add (*histogram*) to highlight the spread among their fluxes. Bad pixels are denoted by bold symbols.

This rather than the mean of the bin's wavelength range minimizes any degradation of the spectral resolution, but results in an irregularly spaced wavelength grid. Bins that lack good data are not assigned either flux or wavelength values at this point.

This co-added spectrum is then reinterpolated to the wavelength scale of each individual spectrum. Points in the individual spectra that differ by more than 3 times their estimated error from this interpolated spectrum are flagged as bad data before the co-addition is repeated.

A final adopted flux vector is created by linearly reinterpolating the binned flux vector to align with the bin centers, restoring a uniform wavelength scale. Bins that lack good data points are now assigned interpolated values and flagged as containing bad data.

Our co-addition procedure was checked by using routines developed by the *IUE* Data Analysis Center. Although often the results were similar, our method was superior in deriving the radial velocities and in removing artifacts in the final results.

Our co-add procedure is illustrated by Figures 1 and 2 for an example of co-adding six SWP spectra of HR 7775 for the vicinity of the line  $\text{Au II } \lambda 1740$ . Figure 1 compares the individual *IUE* observations to the final co-added spectrum, which is shown in each panel by the solid line histogram. The open circles show the original wavelength and flux values that are tabulated in the NEWSIPS mxhi files. The small filled circles show the same data after they are aligned in wavelength and normalized to a common flux scale. The aligned data points that were flagged as bad in the original NEWSIPS data file are marked with a cross.

The locations on the detector of the original spectra were shifted slightly along the dispersion direction with respect to one another. This allows the effect of the reseau mark near  $1737.5 \text{ \AA}$  to be mostly removed, with all but one bin in the final co-added spectrum for this region having at least one good data point included. The bin that does not include any good data points is marked by a short vertical line in the figure, and its value was interpolated from adjacent bins.

Since for each image, the flux is scaled by a single overall normalization factor, any wavelength dependant throughput changes or nonlinearities that were not properly corrected by the NEWSIPS data reduction may result in localized

TABLE 1  
*IUE* SPECTROGRAMS USED IN CO-ADDITIONS

Star	Spectrogram
HR 3383.....	SWP (44436 and 44437), orders 69–125 SWP 44437 orders 66–72  LWP 22853, only spectrum for long-wavelength region
$\kappa$ Cnc .....	SWP (14052, 14047, 15697, 15805, 15830, 24802, 24815, and 24835), orders 66–72 SWP (14052, 14072, 14079, 15697, 15805, 15830, 24802, 24803, 24804, 24805, 24814, 24815, 24825, 24835, and 24836), orders 69–125  LWP (03552, 05113, 05136, and 05144), orders 76–93 LWP (03522, 05113, 05114, 05115, 05122, 05123, 05135, 05136, 05143, and 05144), orders 69–78 and 91–127
$\chi$ Lup .....	SWP (48507, 48508, and 48509), orders 66–72 SWP (48507, 48508, 48509, 48510, 48511, and 48512), orders 69–80 SWP (48507, 48508, 48509, 48510, 48511, 48512, 48515, 48516, and 48517), orders 78–125  LWP (26253, 26254, 26255, 26256, 26257, 26258, 26259, and 26260), orders 75–94 LWP (26253, 26254, 26255, 26256, 26257, 26258, 26259, 26260, 26262, 26263, and 26264), orders 69–77 and 92–127
HR 7775.....	SWP (57338, 57339, and 57344), orders 66–72 SWP (06884, 57338, 57339, 57344, and 57345), orders 69–78 SWP (06884, 06885, 57338, 57339, 57344, and 57345), orders 76–125  LWP (32336, 32339, 32340, and 32341), orders 69–127

misalignments of the flux level. For example, in Figure 1 it can be seen that the adopted normalization sets the mean flux level for SWP57344 about 7% too high between  $\approx 1738.3$  and  $1740 \text{ \AA}$ . We have made no effort to correct for such localized flux misalignments.

The individual aligned and flux normalized spectra are compared to the final co-add (*solid line histogram*) for the same six data sets shown in Figure 2. Here all observations are plotted on one panel, with a different symbol type used for each observation. Symbols for the data points flagged as bad in the original NEWSIPS data file are plotted in bold. In Table 1 we list combinations of co-added spectra for four stars treated in § 5 for the abundance of gold.

#### 4. ATMOSPHERIC PARAMETERS

An essential step in the systematic generation of synthetic spectra for this study is the determination of the stellar atmospheric parameters effective temperature ( $T_{\text{eff}}$ ), gravity ( $g$ ), projected equatorial rotational velocity ( $v \sin i$ ), microturbulent velocity ( $\xi$ ), and the derived abundances of the iron-group elements (Fe/H) for all of our targets. Most stars observed by the *IUE* are bright and have been previously studied by photometric and/or spectroscopic means. Adelman et al. (2002) and Adelman & Rayle (2000) compared published spectrophotometry with their own  $H\gamma$  profiles for many normal B and A stars and HgMn stars, respectively, with the predictions of ATLAS9 model atmospheres (Kurucz 1993). Furthermore, they compared their results with the photometric calibration of Napiwotzki et al. (1993) for the *uvby*- $H\beta$  photometric system and found slight discrepancies in  $T_{\text{eff}}$  and  $\log g$  (the latter for HgMn stars only). We adopted their values as starting values for the stars in common and for the other stars applied the small systematic offsets to the photometrically determined values. The remaining three parameters [ $v \sin i$ ,  $\xi$ , (Fe/H)] are best determined from high-dispersion spectroscopic studies. For some of our stars modern spectroscopic analyses already exist (see

Table 2). For the remaining stars we find initial values for the microturbulence by examining the trends of such values. Thus, for the HgMn stars,  $\xi$  is close to  $0 \text{ km s}^{-1}$ , and this value was adopted. For the normal, main-sequence band stars with temperatures greater than  $10,250 \text{ K}$  their microturbulence is  $0 \text{ km s}^{-1}$ , for those with temperatures between  $10,250$  and  $9500 \text{ K}$  it is  $1 \text{ km s}^{-1}$ , and for those with temperatures less than  $9500 \text{ K}$  it is  $2 \text{ km s}^{-1}$ . A. F. Gulliver & S. J. Adelman (2004, in preparation) have found that their values of  $v \sin i$  obtained with  $2.4 \text{ \AA mm}^{-1}$  spectra from the Dominion Astrophysical Observatory as measured using the program VLINE (Hill et al. 1982) give values consistent with those of other high-quality studies.

#### 5. SYNTHETIC SPECTRA

For each star a model atmosphere was generated for our initial atmospheric parameters using the ATLAS9 code (Kurucz 1993). For metal-rich stars such as the Am stars, model atmosphere generation and abundance determination may be an iterative process to arrive at self-consistent models. This is generally only important for large abundance deviations from the solar values for elements important to opacity, such as helium and carbon, or in the case of Am stars where the rare-Earth and heavier elements may be enhanced by several orders of magnitude.

The synthetic spectra were generated using the SYNTH program (Kurucz & Avrett 1981; Kurucz 1993), which is part of the ATLAS9 suite of programs. The bulk of the line list data was taken from the data base compiled by Kurucz & Bell (1995). Alterations to these lists were made as corrections to wavelengths and  $gf$ -values, as well as the inclusion of new lines, for cases of new or improved laboratory or theoretical data and will be discussed as the individual elements are presented. For the iron-group elements the line lists contain wavelengths from experimentally determined energy levels, and oscillator strengths as calculated from a Cowan code (Cowan 1981). The accuracy of the  $f$ -value calculations is known to be somewhat dependent upon excitation energy. For higher excitation states, where the

TABLE 2  
TABLE OF OPTICAL REGION SPECTROSCOPIC STUDIES

Star	Reference
Hot Am Stars	
$\theta$ Leo, o Peg .....	A. F. Gulliver & S. J. Adelman (2004, in preparation)
$\pi$ Dra .....	Adelman (1996)
$\phi$ Aql .....	Caliskan & Adelman (1997)
$\sigma$ Aqr .....	Adelman & Albayrak (1998)
60 Leo .....	Adelman et al. (1999)
Normal Stars for Am Stars	
Vega .....	Adelman & Gulliver (1990)
2 Lyn .....	Caliskan & Adelman (1997)
$\lambda$ UMa .....	Adelman (1999)
Normal Stars	
$\pi$ Cet, 134 Tau, 21 Aql, $\nu$ Cap .....	Adelman (1991)
$\gamma$ Peg, $\iota$ Her .....	Pintado & Adelman (1993)
$\xi$ Oct .....	Adelman et al. (1993a, 1993b)
7 Sex .....	Adelman & Philip (1994)
$\kappa$ Cep .....	Adelman (1996)
$\gamma$ Gem .....	Adelman & Philip (1996)
$\zeta$ Dra, $\eta$ Lyr, 8 Cyg, 22 Cyg .....	Adelman (1998)
$\alpha$ Dra, $\tau$ Her .....	Adelman et al. (2001a)
17 And .....	Kocer et al. (2003)
$\alpha$ Sex .....	Pintado & Adelman (2003)
HgMn Stars	
53 Tau .....	Adelman (1987)
HR 7664 .....	Adelman (1988)
$\nu$ Cnc, $\iota$ CrB, HR 8349 .....	Adelman (1989)
HR 7361 .....	Adelman (1992)
HR 4072, HR 7775 .....	Adelman (1994), Wahlgren et al. (2000)
$\chi$ Lup .....	Wahlgren et al. (1994a)
HR 89, 33 Gem .....	Adelman et al. (1996)
112 Her .....	Ryabchikova et al. (1996)
$\mu$ Lep, $\kappa$ Cnc, 28 Her, HR 4817, 3 Cen A .....	Adelman & Pintado (2000)
$\nu$ Her, $\phi$ Her .....	Adelman et al. (2001b)

energy separation between states is comparable to the error in determining the excitation value, an incorrect labeling of terms can lead to large errors in the calculated  $f$ -values as a result of configuration interaction. For elements outside of the iron group the Kurucz database is comprised of a mixture of computed and experimentally determined  $f$ -values. Therefore, we have utilized the critically compiled experimental  $f$ -value data of Fuhr et al. (1988) and Martin et al. (1988), other compilations from NIST, and recent high-quality studies whenever possible.

The atomic data (wavelengths, oscillator strengths, energy levels, isotopic shifts, and hyperfine structure) appropriate for the analysis of specific heavy element lines are taken from several studies that have already been published by us regarding the analysis of CP stars using *Hubble Space Telescope* spectra obtained with the Goddard High Resolution Spectrograph. These studies, including ions of platinum (Wahlgren et al. 1995; Kalus et al. 1998), gold (Wahlgren et al. 1995), mercury (Wahlgren et al. 1995; Proffitt et al. 1999), thallium (Johansson et al. 1996; Leckrone et al. 1996), and bismuth (Wahlgren et al. 1994b, 2001; Henderson et al. 1996; Dolk et al. 2002), discuss problems associated with line blending as observed at high spectral resolution as well as the goodness and corrections of atomic data for lines blended with the ion lines of interest. The

effects of hyperfine structure and isotopic shifts are also included into the heavy element atomic line data. However, we do not anticipate being able to derive any meaningful isotope mixture information from the *IUE* spectra, owing to an insufficient spectral resolution and low S/N.

The determination of elemental abundances is made through the comparison of synthetic with observed spectra. Having determined the stellar model atmospheric parameters and assembled the requisite atomic data, the only remaining variables are the stellar rotational velocity,  $v \sin i$ , the atmospheric microturbulent velocity,  $\xi$ , and the abundance of the element of interest. Rotational velocities have been determined as part of the line profile fitting procedure, either from the *IUE* data directly, or from higher spectral resolution data available to the authors, or from published literature. For those stars of normal, or solar-like, chemical composition, it is anticipated, through synthetic spectrum modeling, that lines of the heaviest elements will not be prominent. Thus, to these abundance determinations will be attached a larger error as a result of the greater influence of line blending and noise on weak spectral features. Still, the derived abundances for these stars should indicate whether a general trend exists for late-B type stars to be enriched in heavy elements over the solar system values.

The treatment of stars known to be binary was a consideration when creating the co-added spectra. A relatively high percentage of HgMn stars are known to be binary and pertain to a range of flux ratios ( $L_{\text{pri}}/L_{\text{sec}}$ ) at ultraviolet wavelengths that span from the secondary providing an unobservable flux to the significant. In general, for binaries with few spectra and uncertain orbital characteristics, or stars not known to be binary, the mixing of data from different phases can influence the abundance determinations by a greater amount than the uncertainty of the continuum placement.

### 5.1. Example: The Treatment of Au II

We demonstrate the determination of elemental abundances from *IUE* co-added high-dispersion spectra using the element gold. The determination of the gold abundance in stellar atmospheres has been limited to few chemically peculiar star types, where it has been shown to be enhanced to levels up to 5 orders of magnitude above the solar system value and commensurate with its neighbors in the periodic table, platinum and mercury, for HgMn stars.

Our search for useful spectral lines of Au II began with the study of Rosberg & Wyart (1997). This work presents laboratory measurements for wavelengths throughout the UV and optical regions for many lines, and supplements with theoretically determined  $gf$ -values. We were able to identify three Au II lines in the spectrum of HR 3383 that were reasonably resolved from blending lines. Other lines in this region were deemed unusable as a result of their weakness or line blending. For the HgMn star  $\chi$  Lup additional lines were identified in its spectrum. The prime line for our gold abundance analyses is Au II  $\lambda 1740$ , as it is the strongest by  $gf$ -value, it is resolved from serious blending in high-resolution *HST* spectra of sharp-lined CP stars, and it is not contaminated by elements seen only in CP stars. The study of gold is best conducted at ultraviolet wavelengths since at optical wavelengths the lines from Au II or Au III are fewer, weaker, and currently without experimental oscillator strengths.

We constructed a line list to cover the wavelength region 1740–1760 Å, the extent of the GHRS data for three of our stars. For easement of the continuum placement for the *IUE* spectra a longer baseline is required than for working with *HST* high-resolution spectra. The Kurucz compilation of atomic line data in this region was supplemented by data for several elements important to both the immediate problem of line blending with the Au II line(s) and defining the continuum level. These spectral studies included Fe II (Nave et al. 1997), Fe III (Ekberg 1993), Cr III (Ekberg 1997), Y II (Nilsson et al. 1991), Ni II (Fedcheck & Lawler 1999), and Pt I/II/III (Sansonetti et al. 2003, originally published as Sansonetti et al. 1992). In addition, the known spectra of other first ions were checked for lines in this area, but none were found to contribute to observable features. A correction was made to the published  $gf$ -values of individual hyperfine structure components presented by Wahlgren et al. (1995). There is a discrepancy in that work between the (correctly specified) total  $gf$ -value for the Au II  $\lambda 1740$  line and the summation of the individual  $gf$ -values presented in Table 5 of that work. The net effect of using the incorrect  $gf$ -values for the individual components is to raise the total  $gf$ -value, leading to a decrease of the derived gold abundance by about 0.7 dex.

From our fitting of the *IUE* co-added spectra we can make a general statement related to the abundance uncertainties. A conservative estimate to the agreement in the abundance determination, as given by a comparison of independently

fitting the gold features in the *HST* and *IUE* spectra, using the same atomic line data and model atmospheres, is found to be  $\pm 0.1$  dex for the case of high gold abundance. The uncertainty increases to  $\pm 0.2$  dex for smaller enhancements, as exemplified by the star HR 3383. The use of a single (un-co-added) spectrum will lead to higher uncertainties. Also, an uncertainty of 5%–7% in the placement of the continuum can influence the abundances by up to 0.2 dex. For the case of small abundance enhancements of gold (HR 3383), where line blending can be more influential on a weak line, the wavelength uncertainty for a best fit could be  $\pm 0.1$  Å. This level of uncertainty in wavelength is less than the *IUE* point spacing. Turning the problem around, an uncertainty of a couple tenths of a dex can be realized by a wavelength uncertainty of  $\pm 0.1$  Å.

The four stars having high-resolution ultraviolet spectra are illustrative of how line blending changes over the  $T_{\text{eff}}$  range for HgMn stars. The inclusion of the hot-Am star HR 3383, which has the lowest  $T_{\text{eff}}$  of the four stars, can be used to detect underlying absorption from previously unknown lines since its abundance pattern for very heavy elements is less extreme. We discuss the results for each of these stars.

#### 5.1.1. $\chi$ Lup

$\chi$  Lupi (=HD 141556, B9.5 V HgMn + A2 Vm) is a bright ( $V = 3.95$  mag) double-lined spectroscopic binary system comprised of two chemically peculiar stars. It has been well studied for elemental abundances at both optical (Wahlgren et al. 1994a) and ultraviolet (Leckrone et al. 1999) wavelengths. The ultraviolet analysis, more commonly known as the  $\chi$  Lupi Project, is based on high-resolution spectra obtained with the GHRS on board the *HST*. The atmospheric parameters used in the modeling of both stars are from Wahlgren et al. (1994a). The treatment of the two components in the synthetic spectrum co-addition process accounts for both their wavelength-dependent light ratio (Brandt et al. 1999; Leckrone et al. 1999) and the time-dependent wavelength separation of a given feature. The result presented here is an update of an earlier analysis on gold abundances for  $\chi$  Lup and  $\kappa$  Cnc (Wahlgren et al. 1995), now using corrected  $gf$ -value data for hyperfine components of the Au II  $\lambda 1740$  line.

Regarding its binary properties, the  $\chi$  Lup secondary makes a flux contribution of approximately 13% at 2000 Å, which produces distortions of the line profiles over the orbital period of 15.25 days. Fortunately, our nine *IUE* SWP images were taken over a period of 27 hr, or 7% of the orbital period, near phase 0 of the radial velocity curve. From the orbital analysis by Dworetzky (1972), the wavelength separation for a spectral line located near 1740 Å between the two stars varied continuously from +0.70 and +0.78 Å over the time interval of the data. Co-addition of these spectra and the use of the wavelength separation of +0.74 Å provided good fits to the Au II  $\lambda 1740$  line. The effect of orbital phase choice upon the synthetic spectrum is illustrated in Figure 3, where it can be seen that both the local continuum and line depth are influenced by the orbital phase.

Figure 4 presents the comparisons of observed spectra from the GHRS (Fig. 4a) and *IUE* (Fig. 4b) with synthetic spectra for the abundances of gold that represent the solar system value and the best fit to the Au II  $\lambda 1740$  line in the GHRS spectrum. Table 3 lists the best-fit gold abundance for the stars discussed in this paper. We have been able to model most lines in the GHRS spectrum that contribute to the feature in the *IUE* spectrum at 1740 Å. Line identifications for most of these lines are found in Brandt et al. (1999). The same abundances have been used in the modeling of the *IUE* spectrum presented in Figure 4b. It is clear from the two comparisons that the areas of



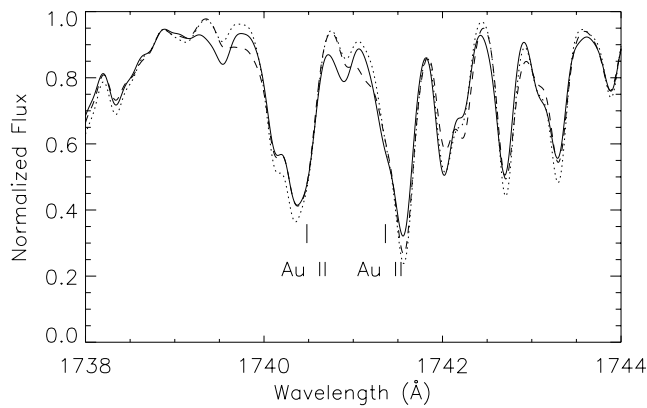


FIG. 3.—Binarity and the *IUE* spectrum of  $\chi$  Lup. Three synthetic spectra, computed for the resolving power of the *IUE* co-add spectrum but reflecting different orbital phases of the binary, are compared. The wavelength separation ( $\Delta\lambda = \lambda_{\text{pri}} - \lambda_{\text{sec}}$ ) between the two components represents the epochs of the *IUE* observation ( $\Delta\lambda = +0.74$  Å, *solid line*), the GHR observation ( $\Delta\lambda = +0.451$  Å, *dashed line*), and the arbitrary assumption ( $\Delta\lambda = +0.00$  Å, *dotted line*) that one might make in the absence of orbital information. The gold abundance representative of the best fit to the GHR spectrum has been used in the calculations, and the locations of the two Au II lines are labeled.

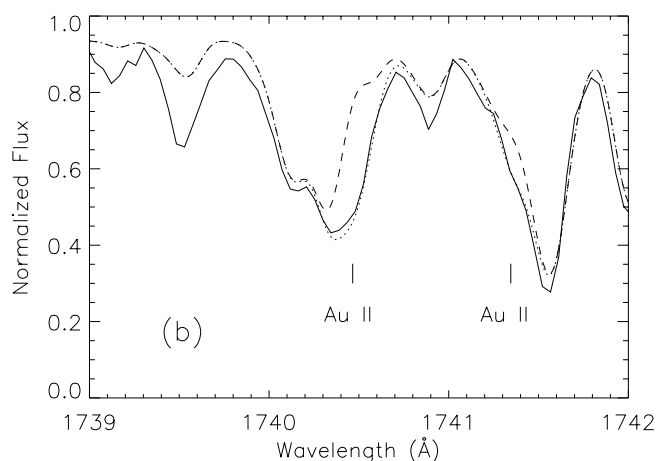
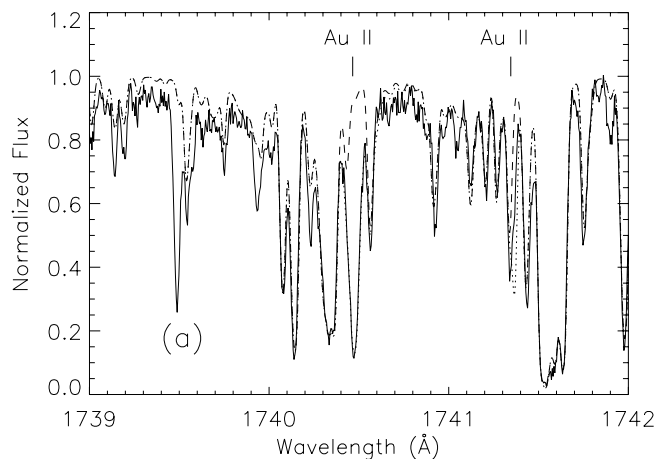


FIG. 4.—Gold in the spectrum of  $\chi$  Lup. In (a) the *HST* GHR high-resolution ( $R = 82,700$ ) spectrum (ID Z01X010R) (*solid line*) is compared with synthetic spectra generated for the solar abundance (*dashed line*) of gold and an enhancement of 4.80 dex (*dotted line*). In (b) the same synthetic spectrum conditions are used for comparison with the co-added *IUE* spectrum.

TABLE 3  
STELLAR PARAMETERS

Star	$T_{\text{eff}}$ (K)	$\log$ ( $g$ )	$v \sin i$ ( $\text{km s}^{-1}$ )	$\log$ $N_{\text{Au}}$
$\kappa$ Cnc A .....	13470	3.8	6.5	5.15
$\kappa$ Cnc B .....	8500	4.0	40.	...
HR 7775 .....	10750	4.0	2.0	6.07
$\chi$ Lup A .....	10680	3.9	0.0	5.77
$\chi$ Lup B .....	9200	4.2	2.0	...
HR 3383 .....	9750	4.0	6.5	2.77
Sun .....				0.83 <sup>a</sup>

<sup>a</sup> Lodders 2003.

poor fitting of the *IUE* data correspond to the unmodeled spectral lines observed in the higher resolution spectrum. This level of goodness of fitting is noticeable in the results for the other three stars.

### 5.1.2. HR 7775

HR 7775 (=HD 193452, B9.5 III–IVp Hg) is a chemically peculiar star of the HgMn type. Its atmospheric parameters and general abundance pattern (Wahlgren et al. 2000) are

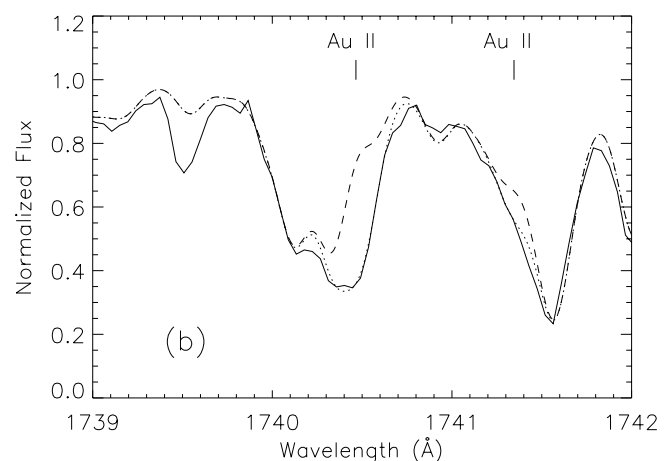
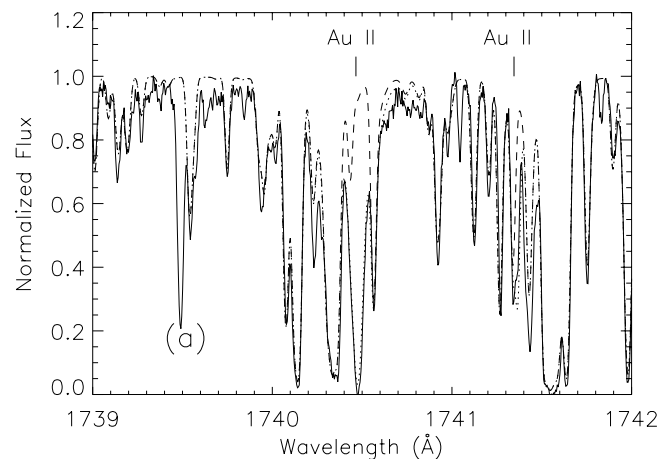


FIG. 5.—Gold in the spectrum of HR 7775. In (a) the *HST* GHR high-resolution ( $R = 82,700$ ) spectrum (ID Z3650207) (*solid line*) is compared with synthetic spectra generated for the solar abundance (*dashed line*) of gold and an enhancement of 5.10 dex (*dotted line*). In (b) the same synthetic spectrum conditions are used for comparison with the co-added *IUE* spectrum.

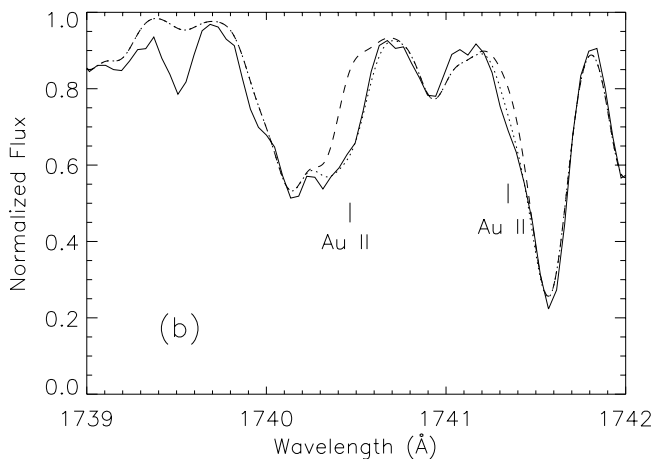
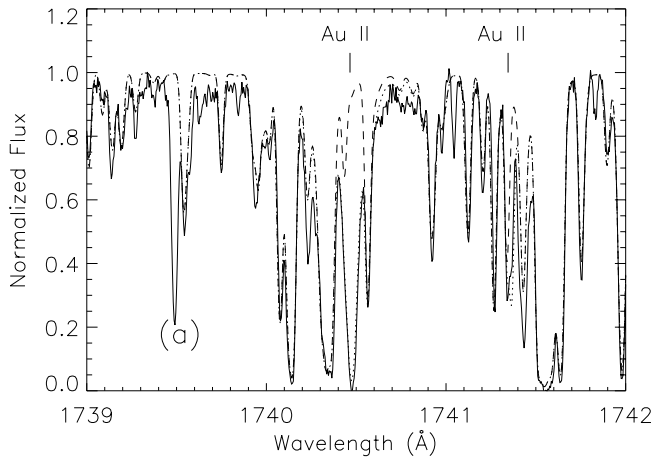


FIG. 6.—Gold in the spectrum of  $\kappa$  Cnc. In (a) the *HST* GHRS high-resolution ( $R = 82,700$ ) spectrum (ID Z0WK0109) (solid line) is compared with synthetic spectra generated for the solar abundance (dashed line) of gold and an enhancement of 4.18 dex (dotted line). In (b) the same synthetic spectrum conditions are used for comparison with the co-added *IUE* spectrum.

similar to that of  $\chi$  Lup A. Both stars also present an isotopic composition for mercury, from the Hg II  $\lambda 3984$  line, that reflects the prominence of the heaviest two isotopes, although the relative contributions of these two are very different.

HR 775 is considered to be a binary (for discussion see Dolk et al. 2003). However, the three magnitude difference at optical wavelengths translates into an undetectable contribution to the flux at UV wavelengths from the suspected secondary. In addition, the orbital parameters of the system are unknown. Therefore, we chose not to include the secondary star in our modeling. The GHRS spectrum is well fit in the immediate vicinity of both Au II lines (Fig. 5) for HR 775.

#### 5.1.3. $\kappa$ Cnc

$\kappa$  Cnc (=HD 78316, B8 HgMn) is also a double-lined spectroscopic binary at optical wavelengths. The light ratio has been determined to be 11.5 in the  $V$  band (Ryabchikova et al. 1998). The suspected light ratio at ultraviolet wavelengths is even higher, and we estimate that the secondary would contribute on the order of 1% to the observed flux. Because of the large uncertainties in our knowledge of the nature of the secondary star, we have modeled the spectrum by considering only the primary star.

An earlier analysis of the gold abundance from GHRS spectra (Wahlgren et al. 1995) provided an enhancement of

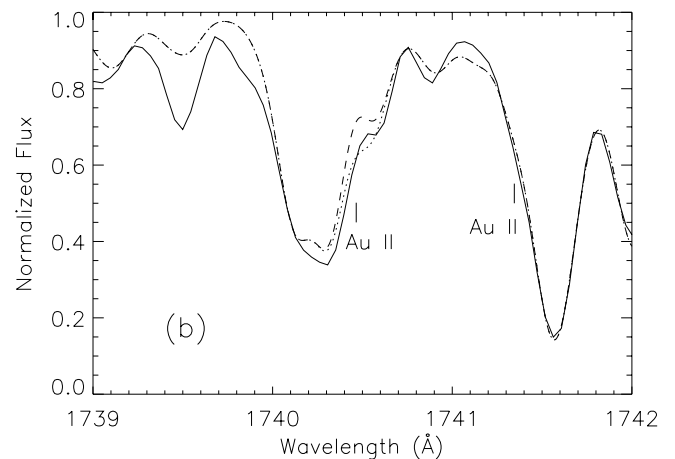
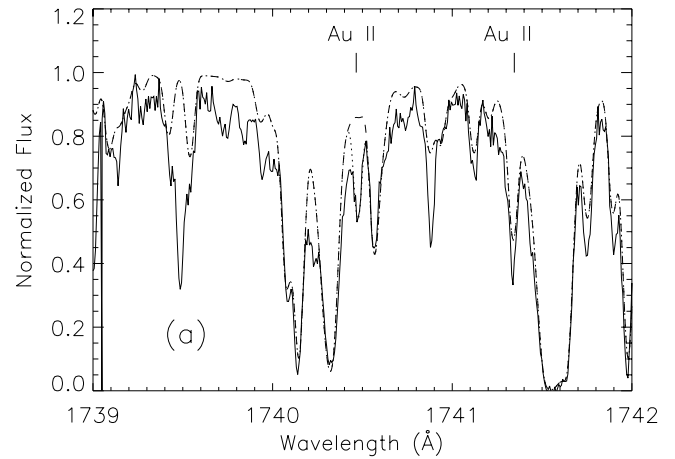


FIG. 7.—Gold in the spectrum of HR 3383. In (a) the *HST* STIS high-resolution ( $R = 90,000$ ) spectrum (ID O6G403010) (solid line) is compared with synthetic spectra generated for the solar abundance (dashed line) of gold and an enhancement of 1.90 dex (dotted line). In (b) the same synthetic spectrum conditions are used for comparison with the co-added *IUE* spectrum.

3.43 dex relative to the solar system abundance. From these same GHRS spectral data we have now updated the abundance to a value of  $\log N_{\text{Au II}} = +5.15$ , reflecting the correction to the  $gf$ -values of the individual hyperfine components. Figure 6 shows the presence of both Au II lines to be detected. Essentially all spectral features comprising the blended features between 1740 and 1742 Å in the *IUE* spectrum are modeled in the GHRS spectrum and in particular the immediate vicinity of the Au II  $\lambda 1740$  line ( $\pm 0.3$  Å), which might have an impact on the line interpretation. This gives us reason to believe that the *IUE* spectra for both hotter and cooler HgMn stars can be properly treated for line blending in our analysis.

#### 5.1.4. HR 3383

HR 3383 (=HD 72660, A1 Vm) has been observed on several occasions with the *HST*. As a hot metal-rich A star its Fe II spectrum is particularly useful for studies of both stars and galaxies. To our delight we are clearly able to identify the Au II  $\lambda 1740$  line and derive an abundance enhancement of 1.9 dex. This is the first identification of a gold line in an Am star and represents an important data point in studying the behavior of the gold abundances to temperatures that are cooler than the traditional cool HgMn stars (spectral type

B9.5). The subject of Am star elemental abundances will be taken up in a forthcoming paper in this series. From Figure 7a and unpublished comparisons between observed and synthetic spectra we note that many weak lines are unidentified or lack the appropriate atomic data to be included in the calculations. The effect of missing line opacity is also noted in the co-added *IUE* spectra, as for example in Figure 7b, where we see that an abundance enhancement of approximately 1 dex is detectable but may not be noticed depending upon the S/N of the data and continuum placement. The Au II  $\lambda 1741.5$  line is not strong enough to be observed at this abundance level, and we also note a limit to the level of abundance enhancement (in the case of the Au II  $\lambda 1740$  line) that might be reasonably ascertained from *IUE* data. Such a level was hinted at in the work of Smith (1997), where his Figure 9 shows the abundance of mercury in normal stars to lie near a value equivalent to an enhancement of 1 dex. In effect, this plateau may signal the level at which an abundance enhancement can be detected from *IUE* data or, of more interest, a level of abundance in stars younger than the Sun.

## 6. SUMMARY

We have inaugurated a project to investigate the abundances of the heaviest stable elements in the atmospheres of normal and chemically peculiar late-B and early A-type main-sequence stars from archival *IUE* high-dispersion spectra. This first installment describes the motivations and methods devised in producing a data set of increased S/N spectra by a process of co-adding multiple *IUE* spectra for HgMn stars. In this manner the S/N can be increased by up to a factor of 3 times the value of

any individual spectrum and the influence of bad pixels can be reduced.

Using usual synthetic spectrum techniques we have demonstrated that *IUE* spectra can be used to extract elemental abundances to a relatively high accuracy when the line blending is properly modeled. *HST* high-resolution spectra for four sharp-lined stars, the HgMn stars  $\chi$  Lupi,  $\kappa$  Cnc, and HR 7775, along with that of the hot-Am star HR 3383 have been studied for spectral line blending, and this knowledge has been transferred to the analysis of lower resolution *IUE* spectra for the same stars. It is shown that with this a priori knowledge the synthetic spectrum fitting to the *IUE* spectra in the vicinity of the Au II  $\lambda 1740$  resonance line reproduces the abundances extracted from the high-resolution data. For the hot-Am star HR 3383, the abundance of gold has been determined for the first time, showing a 1.9 dex enhancement over the solar system value. The goodness of the fits to the *IUE* spectra give us confidence that abundances can be equally well determined for the larger sample of stars and will serve as an important data set in the analysis of B type stars.

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