Peculiar Versus Normal Phenomena in A-Type and Related Stars
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EXPLORING ABUNDANCE AND ISOTOPE ANOMALIES IN CP STARS WITH THE HST/GHRS: HIGH RESOLUTION UV SPECTROSCOPY OF χ LUPI

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ABSTRACT We are using the HST/GHRS in a long-term program to obtain UV spectra of unprecedented resolution and precision for bright, ultra-sharp-lined B_p (HgMn) stars and comparable normal stars. To date we have doubled the number of heavy elements for which abundances may be estimated in χ Lupi, and have obtained the first observations of Hg III lines with which to test diffusion scenarios for its extreme Hg isotope anomaly.

INTRODUCTION

We have a relatively complete knowledge, across the periodic table, of the abundances of the chemical elements in only one star - the sun (Anders and Grevesse 1989). For the older stellar populations of the galaxy there is a fair knowledge of elemental abundances due primarily to the rich visible-wavelength spectra of the neutral atoms and molecules which prevail in the photospheres of late-type stars. Spectroscopists have successfully used photospheric abundances of cool stars to obtain direct evidence of interior nucleosynthesis and dredge-up in evolved stars, and as a tracer of galactic evolution over a wide range of [Fe/H] (e.g., Truran 1991).

In contrast, for the youngest populations of our galaxy, we have a poor overall knowledge of the abundances of the elements. Abundances measured in the interstellar gas are drastically modified by depletion onto grains, the composition of which cannot be directly measured. The photospheric spectra of hot, young O, B and A-type stars tend to be sparsely populated with lines at visible wavelengths, since the strongest spectral transitions of the dominant ionization states occur farther into the ultraviolet as one goes to higher effective temperatures. For any given early-type star, we are fortunate to be able to estimate the abundances of perhaps 15 or 20 elements from ground-based spectra, with demonstrably accurate values (determined, for example, from more than one ionization state) obtainable typically for fewer than 10 elements (e.g., Adelman 1988). One serious consequence of this situation is that we do not know the overall composition of galactic material at the current epoch. We do not know how the the galaxy has evolved in composition over the past several billion years.

The limited available abundance data for early-type stars is sufficient to demonstrate that a substantial fraction of them - perhaps 10 - 20 % of B and A stars, and the large majority of slow rotators - exhibit a bizarre array of abundance anomalies, including anomalies in isotopic composition. Michaud and his colleagues have achieved major successes in ascribing these anomalies to hydrodynamical processes in the outer stellar layers - radiatively-driven diffusion, aided or mitigated by magnetic fields, weak stellar winds, turbulence, and rotational mixing. But, in the absence of comprehensive and accurate observational information about elemental abundances, it is difficult to constrain models of the diffusion process, and the possible contributions of other interesting physical processes remain obscure. The latter may include, 1. nucleosynthetic evolution of the composition of pre-stellar material since the time of the sun's origin, 2. fractionation prior to star formation between gas-phase interstellar material and interstellar grains and 3. interactions (including mass transfer) among companions in multiple-star systems.

High-resolution UV spectroscopy of sharp-lined, early-type stars holds immense promise for improving our knowledge of the abundances of the elements across the periodic table for the young population of the galaxy. For this reason, my team has undertaken a long-term, comprehensive study of the spectra of a small number of carefully selected stars, combining UV data obtained with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) and high quality ground-based observations. Over the next several years we will continue to report new abundance results for these stars with the ultimate expectation of populating a large fraction of the periodic table with reliable values.

For simplicity we are concentrating on non-magnetic, non-variable HgMn stars (e.g., χ Lup, κ Cnc and 53 Tau) and comparable stars with weakly peculiar or "normal" surficial abundances (e.g., γ Gem). The stars are selected for their brightness and very low v sin i values (< 10 km s^{-1}).

In a single GHRS Echelle-mode observation we are limited to a narrow wavelength interval (9-16 A, depending on the wavelength), so that it is impractical to piece together a complete spectrum. However, the information content of these narrow intervals is extraordinarily high, and the time required to fully analyse even a single 10 A interval may be measured in months.

A second problem is that the currently available atomic data, including Kurucz's (1991) enormous and extremely useful data base, is neither sufficiently comprehensive nor sufficiently accurate to allow proper analysis of UV observational data of this quality. Thus, we must rely on the atomic physics community to provide "customized" wavelengths, oscillator strengths, line broadening parameters, and information about isotope splitting and hyperfine structure. There are currently more atomic physicists than astrophysicists working on our team.

In this paper we describe work in progress on testing the predictions of diffusion scenarios for the origin of the Hg isotope and abundance anomalies in χ Lupi and other Hg-rich stars, suggested by Michaud, Reeves and Charland (1974). We also discuss early results of our abundance analysis of χ Lupi, including values obtained for the first time for many species not observed in visible-wavelength spectra.

OBSERVATIONS

To date we have obtained GHRS observations of χ Lupi and κ Cancri in the Echelle-B, Small Science Aperture mode in five wavelength intervals listed in TABLE I. These were selected primarily to provide data on important transitions of Hg I, Hg II and Hg III, to allow us to gain insight into the Hg abundance and isotope anomalies of these stars. The analysis of the data for κ Cancri is at an early stage and will not be discussed here.

The Echelle-A mode of the GHRS, which provides high resolution coverage from about 1150 to 1700 A, is currently (and we hope temporarily) inoperable, so that we are now concentrating on observations from 1700 to about 2700 A. The resolving power (λ/δλ) of the GHRS at these wavelengths ranges from about 80,000 to 90,000. Our data have signal-to-noise ratios in the continuum of approximately 40 to 60, with the exception of the 1942 A interval for χ Lupi, for which S/N $\simeq$ 100.

TABLE I GHRS ECH-B Observations

central λ (A)	interval width (A)	key ion
1742	9.7	Hg III
1849	8.9	Hg I
1942	10.4	Hg II
2354	12.2	Hg III
2542	13.8	Hg I

The target star, χ Lupi, is a double-lined binary. The primary has T_{eff} = 10,650 K, log g = 3.8, V_t = 0.0 km s^{-1}, and v sin i $\simeq$ 1.0 km s^{-1}, based on the analysis of ground-based spectra by Adelman, et al. (1992). The corresponding values for the secondary star are, respectively, 9,200K, 4.2, 2.4 km s^{-1}, and 2.0 km s^{-1}. Our LTE spectrum synthesis calculations model the spectra of both stars and combine them, using the appropriate light ratio and a radial velocity difference from Dworetsky (1972). χ Lupi is a factor of 10^5 overabundant in Hg, at least 99% of which is in the form of ^{204}Hg in the line-forming region (Leckrone, Wahlgren and Johansson 1991), while its Mn abundance is within a few tenths of a dex of the solar value.

The present paper focuses on two spectral intervals listed in Table I, centered on 1942 A and on 1742 A. In addition to important Hg transitions, these intervals are extraordinarily rich in well-resolved transitions of many other species. To illustrate the potential of high-resolution UV spectroscopy of sharp-lined stars, we reproduce in Figure 1 the most up-to-date version of a diagram that has become emblematic of the GHRS program. Although the IUE is a very important tool for astrophysics, its relatively low resolving power and S/N characteristics obscure a great deal of spectroscopic information that becomes immediately evident in the GHRS data. In this single 2 A interval we see for the first time lines of Ru II and Zr III (positive identifications, based on several lines of each species) and of As I and Ge II (tentative, single-line identifications to be verified with future observations at other wavelengths).

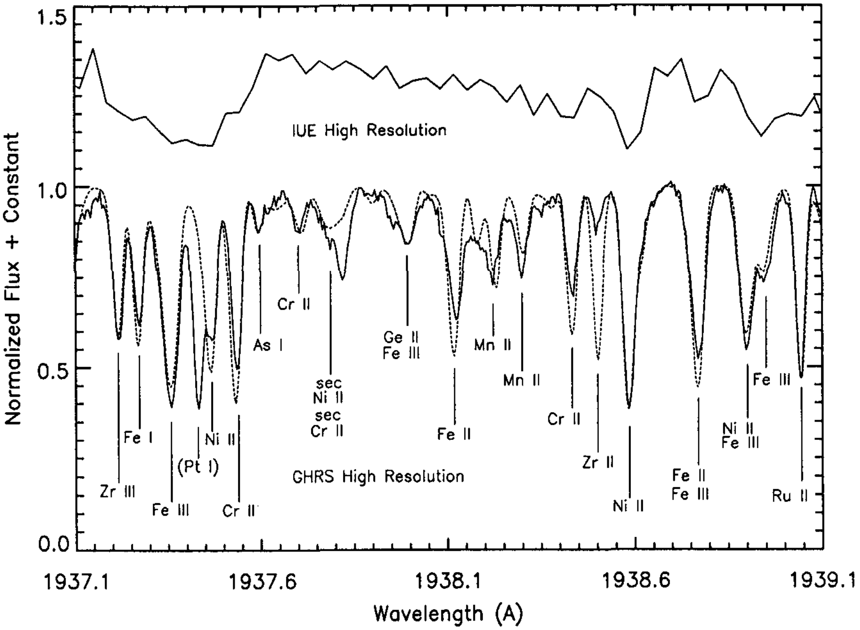

Figure 1. IUE high dispersion (top), GHRS echelle (bottom, solid) and theoretical (dashed) spectra of χ Lupi. Note lines of Zr III, As I, Ge II, Ru II.

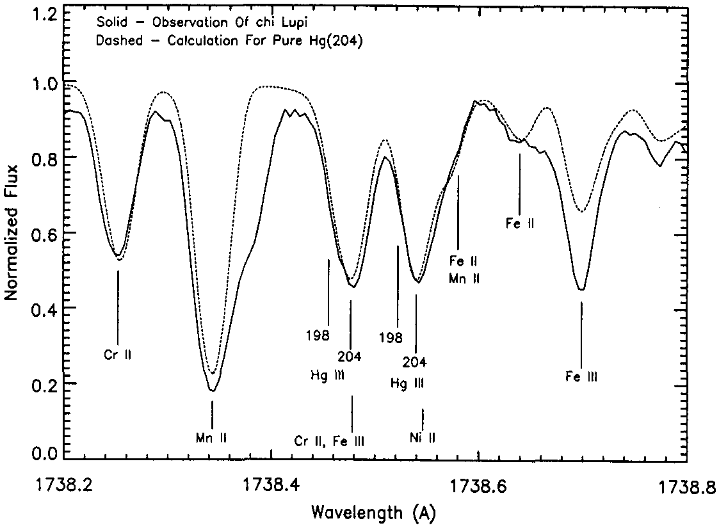

Figure 2. Observed and calculated spectra of χ Lupi near Hg III transitions, λ1738.47 and λ1738.52. New laboratory wavelengths of pure ^{198}Hg and ^{204}Hg are marked.

MEASURING WAVELENGTHS WITH THE GHRS

It is important to emphasize the precision with which relative wavelengths can be measured with the GHRS. With the high resolution and S/N ratio of our data we are able to resolve individual lines of Fe II, Ni II and Mn II, for example, whose wavelengths have been measured in the laboratory, using Fourier Transform Spectrometers, with an absolute accuracy usually exceeding 1 mA. By utilizing such lines to establish or to check the wavelength registration of our observed stellar spectra, we can transfer this level of accuracy to the lines of many other ions observed in the stellar spectrum. The resulting wavelengths derived from the GHRS data are typically much more accurate than those published, for example, in the Ultraviolet Multiplet Tables or similar references.

An excellent example is the case of Ru II. Leckrone, Johansson and Wahlgren (1991) described an early attempt to synthesize three beautifully resolved lines of Ru II observed in the 1942 A interval. The wavelengths used were those of Shenstone and Meggers (1958). The calculations reproduced the relative line strengths quite well, but the calculated profiles were displaced from the observed wavelength in the GHRS spectrum by about 16 mA - a very noticeable shift at this resolution. New measurements of the wavelengths of these Ru II lines were made with an FTS by the Atomic Spectroscopy group at Lund University (Joueizadeh 1992). These are compared to the GHRS wavelengths and to the previously published values in TABLE II.

TABLE II Wavelengths Of Ru II Lines (A)

Published[1]	GHRS	Lund FTS	Lund - SM	Lund - GHRS
1939.056	1939.042	1939.043	-0.013	+0.001
1939.521	1939.506	1939.505	-0.016	-0.001
1943.966	1943.952	1943.950	-0.016	-0.002

Figures 1, 3, and 5 illustrate the revised spectrum synthesis of the three Ru II lines, in which the new Lund wavelengths have been used. The fit is now extremely good.

We encountered similar problems with insufficiently accurate published wavelengths of Fe III, Zr III, Ni II and Mn II. For all of these species we have acquired newly measured laboratory wavelengths which substantially improve the quality of the fit of the synthetic spectrum to the observations. The time has come for a broad campaign to improve the accuracy of published wavelengths for ultraviolet transitions of the lower ionization states of many elements. In the next section we apply the very precise wavelength scales of the GHRS observations to a particular astrophysical problem - the origin of the isotope anomaly of Hg in χ Lupi.

THE Hg ISOTOPE ANOMALY

White, et al. (1976) used high-resolution photographic and Fabry-Perot interferometric observations of the Hg II λ3984 line to reveal substantial departures from the solar-system blend of Hg isotopes in HgMn stars. Their data suggested an effective temperature dependance, with the more extreme isotope anomalies appearing in the cooler HgMn stars, such as χ Lupi. Using GHRS observations of the Hg II resonance line at 1942.3 A, Leckrone, Wahlgren and Johansson (1991) verified that, in χ Lupi's photosphere, at least 99% of all Hg II particles are in the form of ^{204}Hg, the heaviest Hg isotope. They derived an abundance, log N(Hg)/N(H) = -5.9.

Michaud, Reeves and Charland (1974) proposed radiatively-driven diffusion as the mechanism responsible for the Hg abundance and isotopic anomalies in HgMn stars. According to their model, stars like χ Lupi started life with a solar Hg abundance and isotope mixture. In the solar system ^{204}Hg constitutes only 7% of the total abundance of Hg isotopes. The abundance of Hg, integrated over the line forming region of χ Lupi, is 10^5 times higher than the solar abundance, and this is essentially pure ^{204}Hg. Thus, if the mechanism proposed by Michaud et al. is correct, radiatively-driven diffusion must have achieved a total overabundance of Hg in the outer layers of the star of $10^5/0.07 = 1.4 \times 10^6$ relative to the sun.

But what happened to the very large quantity of light Hg isotopes that are now missing from the line forming region -isotopes 198, 199, 200, 201 and 202, adding up to 1.3×10^6 times the solar Hg abundance? Michaud, et al. suggested several alternative scenarios, one of which was particularly intriguing. In this model all the Hg isotopes, predominately in the singly ionized state, are driven by radiation pressure upward in the stellar atmosphere to the point where the ionization balance shifts (due to very low electron densities) in favor of Hg III. Since Hg III is calculated to be only weakly supported by radiation pressure, the upward diffusion of Hg particles is greatly reduced at this point, and Hg accumulates in a thin layer high in the photosphere. Within this layer radiative and gravitational forces are delicately balanced, so that in time the small mass differences among the

Hg isotopes will cause them to segregate. The lighter isotopes will preferentially accumulate at a higher level than the heavier isotopes, and will be predominately in the form of Hg III.

There are no observable transitions of Hg III at visible wavelengths, but a relatively large number occur in the UV. If the light isotopes are "hiding" as Hg III ions this should be evident in observations of both the strengths and wavelengths of the UV Hg III lines. Figure 2 shows our observation of two transitions of Hg III, 1738.47 A (6s $^1D_2$ - 6p $^3P_1$) and 1738.52 A (6s $^3D_2$ - 6p $^3P_2$), in χ Lupi. Because of an almost complete lack of information about the precise wavelengths, isotope structure, and oscillator strengths of the Hg III lines, we have had considerable difficulty synthesizing this spectrum. However, this situation has now dramatically improved.

Sansonetti and Reader (1992) at NIST have completed very accurate wavelength measurements of these Hg III lines for both pure ^{198}Hg, the lightest isotope, and pure ^{204}Hg. The uncertainty in their wavelengths is ± 2 mA, and the uncertainty in the GHRS wavelength scale is also approximately ± 2 mA for the observation shown here. The measured separations between the ^{198}Hg and ^{204}Hg isotopic components of λ1738.47 and λ1738.52 are 22 and 19 mA, respectively.

Figure 2 contains a synthetic spectrum calculated for the case of pure ^{204}Hg, using the new NIST wavelengths and an abundance, log N(Hg)/N(H) = -4.72. The wavelength positions for ^{198}Hg are also shown. Calculations by Brage (1992, private communication) indicate that the isotopic components for the abundant light isotopes, ^{200}Hg and ^{202}Hg, approximately trisect the intervals between ^{198}Hg and ^{204}Hg. The fit to the observed spectrum in Figure 2 is good, and any attempt to synthesize the profiles with an isotope mixture heavily weighted toward the light isotopes is unlikely to yield a satisfactory result. Thus, solely on the basis of the precise wavelengths measured with the GHRS, we can at least tentatively conclude that Hg III exhibits the same isotope anomaly as does Hg II and that the light isotopes are not "hiding" in the form of Hg III.

It is true that the Hg abundance derived from the strengths of the two Hg III 1738 A lines, using oscillator strengths obtained from ab initio Cowan Code calculations, is about a factor of 15 higher than the abundance of Hg derived from the Hg II λ1942.3 resonance line. However, throughout the line forming region, 99% of the Hg particles are singly ionized, and less that 1% are in the form of Hg I and Hg III. It is likely that the ionization balance departs strongly from LTE. We plan to undertake non-LTE calculations for Hg in χ Lupi to test this proposition. It is also very important that diffusion theorists undertake more sophisticated calculations for Hg than were possible in the 1970's. Such efforts are now justified by the quality of our observations.

SPECTRUM SYNTHESIS AND ELEMENTAL ABUNDANCES

We have completed the spectrum synthesis of the λ1942 interval for χ Lupi, limited only by the availability of atomic spectroscopic data, and have performed calculations for a few lines in the λ1742 interval. The calculations utilize the Kurucz LTE code SYNTHE and ATLAS model atmospheres derived by Adelman, et al. (1992) from their analysis of χ Lupi's visible-wavelength spectrum. The abundances of iron-group and other elements obtained from the ground-based observations, together with Kurucz's (1991) most recent data base of semi-empirical oscillator strengths, were used as the starting point for the theoretical calculations.

Lines from iron-group ions are ubiquitous in these spectra and make a dominate contribution to line blending. We found that the accuracy of the Kurucz (Cowan Code) oscillator strengths for iron-group ions (V II, Cr II, Mn II, Fe II, Co II) is highly variable, as indicated by our inability to simultaneously fit many lines of the same ion with a single abundance value. We did not attempt to derive new abundances for these ions from the present data because of the lack of accurate atomic parameters for the particular transitions observed.

We found four transitions of Fe II (λλ1937.114, 1938.652, 1939.426, 1939.698) and one of Cr II (λ1938.058) that are "super-anomalous", in the sense that the line strengths calculated with Kurucz log gf values are far too strong as compared to the observations. This arises from problems in accurately treating configuration interactions and level mixing in Cowan Code calculations (Leckrone, et al. 1990). Since these unrealistically strong calculated lines obscured other interesting features in the synthetic spectrum, we reduced their log gf values by 1 - 2 dex to fit the observed spectrum. Otherwise variances between theory and observations shown here realistically depict the combined uncertainties of the atomic data and the ground-based iron-group abundances. Our preliminary abundance results are as follows.

Zirconium (Z = 40)

Figures 1 and 3 show the synthesis of three well-resolved lines of Zr III - λλ1937.22, 1940.24 and 1941.06. All three features are well matched for log N(Zr)/N(H) = -8.09, with oscillator strengths derived by Redfors (1991). This abundance is 0.65 dex higher than the Zr abundance, -8.74 ± 0.25,

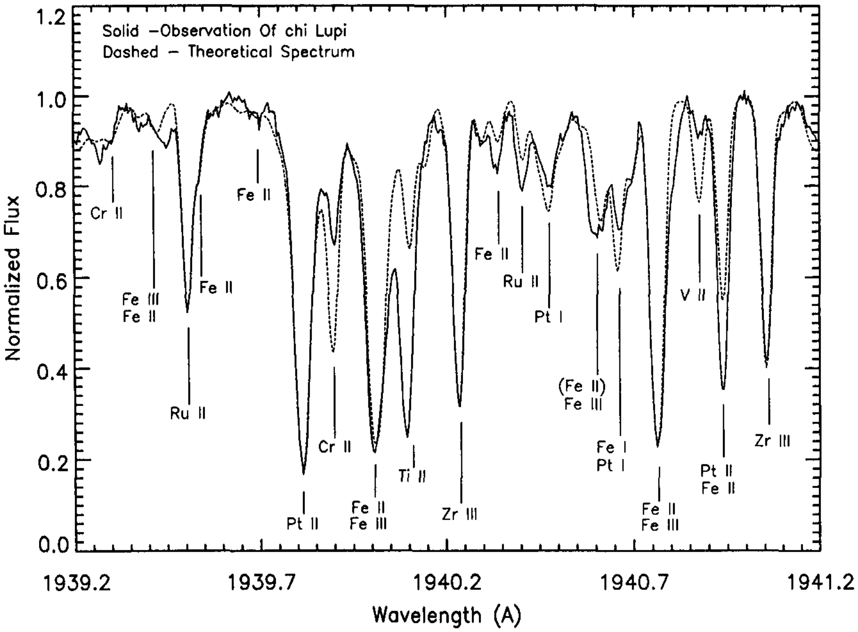

Figure 3. Observed and calculated spectra of χ Lupi, showing synthesis of Ru II, Zr III, Pt II lines.

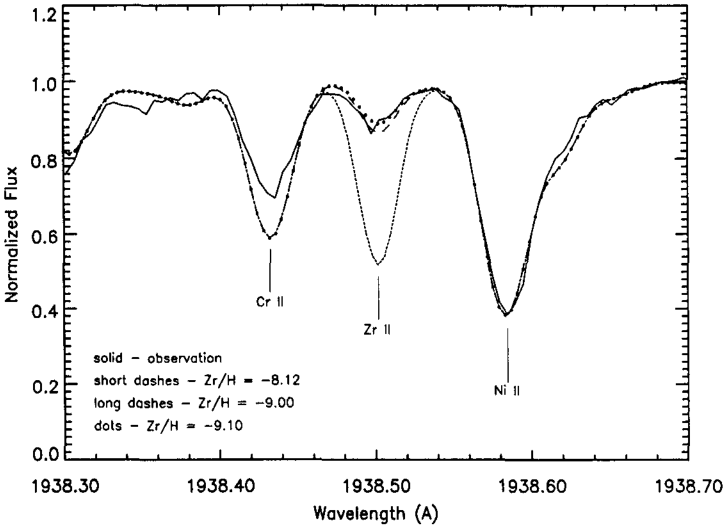

Figure 4. Synthesis of UV Zr II line. Derived abundance agrees with visible-wavelength Zr II lines and is in discord with abundance, -8.1, from UV Zr III lines.

derived from 11 lines of Zr II in the visible-wavelength spectrum. It is +1.31 dex higher than the solar Zr abundance.

Figure 4 illustrates the only line of Zr II seen in the λ1942 interval. Our synthesis of this feature, using a Cowan Code oscillator strength, yields an abundance of approximately -9.0 ± 0.2, consistent with the ground-based result for Zr II. Also plotted is the excessively strong Zr II line calculated with the abundance derived from the Zr III lines.

Both UV and visible-wavelength data yield the same Zr abundance from Zr II lines, which is systematically lower than the abundance obtained from lines of Zr III. The ionization balance between Zr II and Zr III probably departs from LTE. In future observations we will search for similar systematic inconsistencies among ionization states for Sr and Y. Previous investigations of the odd-even abundance pattern in the Sr-Y-Zr triad, of obvious importance for nucleosynthesis scenarios, should be repeated using UV observations of the third spectra (the majority ionization state) and non-LTE spectrum synthesis.

Nickel (Z = 28)

Figure 4 also shows the good theoretical fit to a well-resolved line of Ni II near 1938.58 A, based on the Kurucz log gf value for this transition and the abundance, log N(Ni)/N(H) = -6.08, derived by Adelman, et al. from ground-based observations of three Ni II lines. The only adustment we have made is a slight improvement to the wavelength of the line, based on a recent FTS measurement (Litzen 1991, private communication). This result confirms the abundance of Ni derived from the visible-wavelength observations. The abundance of Nickel in χ Lupi A is 0.33 dex BELOW the solar value.

Copper (Z = 29)

Figure 5 illustrates the spectrum synthesis of Cu II λ1944.597, which is blended with a weak line of Si II at 1944.586 A, but is otherwise well-resolved. The oscillator strength for this Cu II transition is from Kurucz and Peytremann (1975), verified by Kono and Hattori (1982). We obtain log N(Cu)/N(H) = -8.35 for χ Lupi A, 0.56 dex BELOW the solar abundance.

Ruthenium (Z = 44)

Figures 1, 3 and 5 illustrate the good fits achieved for Ru II λλ1939.043, 1939.505, and 1943.950, using oscillator strengths obtained from homologous transitions in Fe II, verified by Cowan Code calculations. The derived abundance is log N(Ru)/N(H) = -7.90, 2.26 dex above the solar abundance.

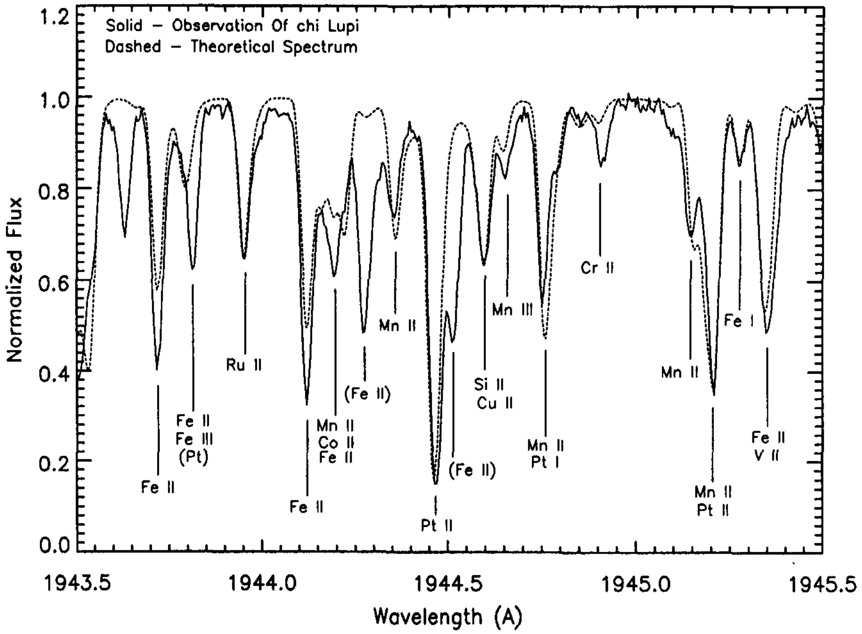

Figure 5. Observed and calculated spectra of χ Lupi, showing synthesis of Cu II, Ru II and Pt II lines. Parentheses denote unclassified transitions.

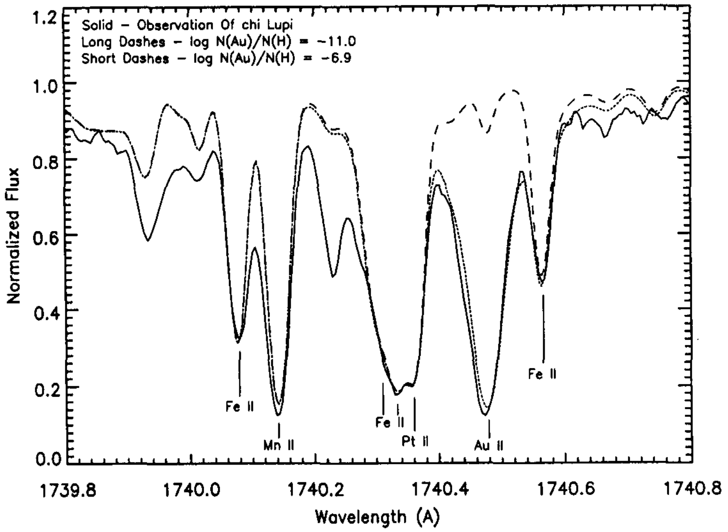

Figure 6. Observed and calculated spectra of χ Lupi, showing the raie ultime line of Au II, λ1740.475. Long dashes denote calculation for solar gold abundance.

Germanium (Z = 32)

Ge II λ1938.007 is the stronger component of a blend with Fe III λ1937.990, illustrated in Figure 1. New wavelengths and oscillator strengths for Fe III transitions have been provided by Ekberg (1991, private communication). These yield substantially improved fits to the observed profiles of the UV Fe III lines, when the ground-based abundance from Fe I and Fe II lines is adopted. Thus, we expect the blend of Ge II and Fe III lines to provide a reasonably accurate abundance for Germanium. We estimated the oscillator strength for the Ge II transition from the homologous transition of Si II and also from the corresponding transition in isoelectronic Ga I. Both approaches gave a consistent value. We obtain log N(Ge)/N(H) = -7.70, which is 0.89 dex above the solar Germanium abundance.

Arsenic (Z = 33)

A weak but reasonably well-resolved line of As I is seen at 1937.594 A in Figure 1. Arsenic has not with certainty been observed previously, even in the solar spectrum. A new oscillator strength for this transition comes from a laser fluorescence lifetime measurement by Bengtsson, et al. (1992) at Lund, with which we derive log N(As)/N(H) = -7.84. This is 1.79 dex over the meteoritic value. However, As I is a minority ionization state at these temperatures and is possibly susceptible to large deviations from LTE in the ionization balance. We hope to undertake a search for lines of As II in future observations.

Gold (Z = 79) and Platinum (Z = 78)

In his Ph.D. thesis Dworetsky (1971) tentatively identified two extremely weak features (10 mA), near the plate limit of his spectra, as Au II. In Figure 6 we show the GHRS observation of the "raie ultime" line of Au II at 1740.475 A. There is no ambiguity about the identification of this strong line of Au II. Also shown are two spectrum synthesis calculations, one for the solar gold abundance, and one for our preliminary best fit with log N(Au)/N(H) = -6.95. The latter is 4.04 dex greater than the solar value. For details see Wahlgren, et al. in these proceedings.

We observe many lines of Pt I, Pt II and possibly Pt III in the UV spectra of χ Lupi A, as illustrated in Figures 1, 3, and 5. Our preliminary analysis, using Cowan Code oscillator strengths, confirms the Pt abundance, -5.95, derived from IUE spectra by Dworetsky, Storey and Jacobs (1984).

Combining these results with the abundance of Hg, -5.92, derived from λ1942.3, we see that the Pt-Au-Hg triad obeys the classical odd-even relation expected in nucleosynthesis. Strikingly (but perhaps coincidentally if diffusion is the responsible mechanism), all three elements are seen in χ Lup A purely in a form produced by r-processing, ^{198}Pt (Dworetsky and Vaughan 1973), ^{197}Au, and ^{204}Hg.

ABUNDANCE TRENDS

Although ours is a long-term study, and the first results reported in this paper are preliminary, it is interesting to begin to look for trends or patterns in the derived abundances over the entire periodic table. So far, with the GHRS observations we have doubled the number of heavy elements ($22 \leq Z \leq 80$) for which abundances in χ Lupi can be estimated, compared to ground-based data alone. Figure 7 illustrates the abundances, relative to solar-system values, for all the elements analysed to date.

Initially we had no information about elements between Ruthenium (Z = 44) and Platinum (Z = 78). As a stopgap we have adopted the equivalent widths of the Ba II resonance line, λ4554.0, published by Dworetsky (1971). We obtain identical abundances for this important s-process element for the two binary components, -8.63 for χ Lupi A and -8.60 for χ Lupi B. These are 1.2 to 1.3 dex greater than the solar value. Ba II is a minority ionization state, however, and we hope soon to obtain UV observations of Ba III.

Some rather clear trends emerge from the data plotted in Figure 7. From Titanium through Iron (Z = 22 - 26) the abundances hover a few tenths of a dex above the solar values. There is a rather shallow abundance "valley" of about one half dex at Nickel and Copper (Z = 28, 29). We do not yet have data for Zinc or Gallium (Z = 30, 31), but beginning at Z = 32 (Germanium) and extending to heavier elements there is a dramatic increase in the magnitude of overabundances. All species between Z = 32 and Z = 56 analysed to date are overabundant relative to the sun by roughly 1 - 2 dex. By the time one reaches Platinum, Gold and Mercury (Z = 78 - 80), the overabundances have grown to 4 - 5 dex.

From the perspective of nucleosynthesis, the elements with large overabundances in Figure 7 represent a mixture of s-process and r-process products. Monoisotopic ^{75}As, ^{198}Pt, ^{197}Au, and ^{204}Hg are all produced in high-neutron-flux environments. On the other hand, Germanium (Z = 32), Strontium (Z = 38), Yttrium (Z = 39), Zirconium (Z = 40), Ruthenium (Z = 44), and Barium (Z = 56), are commonly associated with slow-neutron-capture nucleosynthesis in stellar interiors. Despite their large abundance enhancements, the triad of Pt - Au - Hg preserves the odd-even abundance pattern expected to result from nucleosynthesis. The same odd-even pattern is not in evidence at Sr - Y - Zr. However, as discussed previously, the relative abundances of these species must be considered highly uncertain until full non-LTE analyses resolve the discrepant values derived from different ionization states. We are not aware of an astrophysical scenario in which such large abundance enhancements of both s-process and r-process nuclides could be produced simultaneously by nucleosynthesis (although this does not mean it would be impossible to conceive of one).

To place the magnitudes of these anomalies in perspective, we compare χ Lupi's abundance patterns to those of an average of six S stars from Wallerstein (1984) in Figure 7. In the latter there is, of course, also a dramatic rise in abundances, relative to the sun, of s-process elements. The abundances of Zirconium and Ruthenium in the S stars and in χ Lupi are of similar magnitude. Future GHRS observations of the other important components of this s-process chain, Niobium and Molybdenum, are planned. It would be of interest to further compare and contrast these very different types of chemically enriched stellar atmospheres, for example by searching for Platinum, Gold and Mercury in S stars, Barium stars, Blue Stragglers, etc.

A different perspective on χ Lupi's abundance patterns may be obtained if we plot the abundance enhancement of each element versus the abundance of that element in the sun, as in Figure 8. Here the data suggest a simple monotonic relation between the magnitude of abundance enhancement and the original pre-stellar abundance of the element in question (suspending for the moment the question of whether solar abundances accurately portray the composition of pre-stellar material for a much younger star). From the viewpoint of diffusion theory such a relation might be understood simply as a result of saturation effects. If all heavy atoms and ions were efficient absorbers and carriers of radiative momentum, then the major factor inhibiting their upward diffusion would be their propensity to self-absorb the flux at the particular wavelengths of their most important line and contiuum transitions. The least abundant species would be the least likely to saturate in this way, and would therefore be the most likely to continue to be driven by diffusion into the photosphere to very high levels of abundance enhancement.

Although the data plotted in Figures 7 and 8 are still too sparse, and in some cases too uncertain, to allow firm conclusions to be drawn, we believe they illustrate the possibilities for elucidating the physical processes at work in the formation of abundance anomalies inherent in comprehensive abundance information over a wide range of atomic number. However, there is one additional interesting complication that must be addressed. We have been forced to quantify abundance anomalies in χ Lupi relative to solar abundances, because we have no information about the

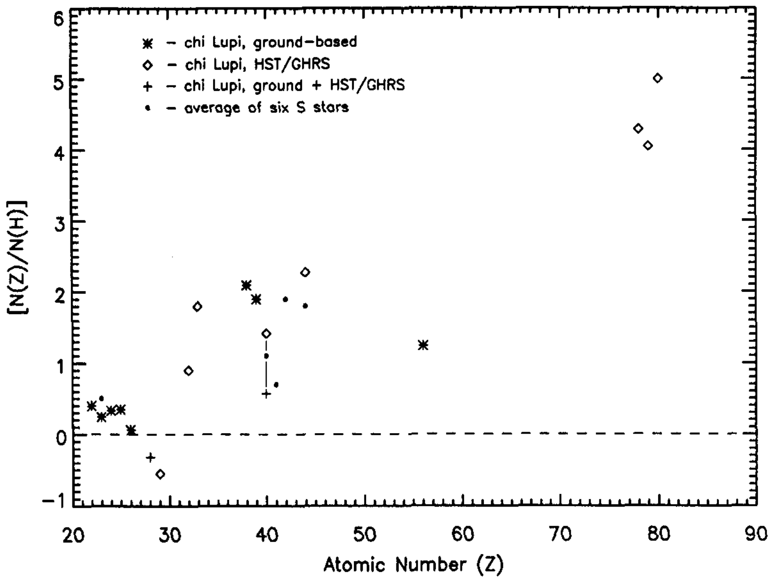

Figure 7. Logarithmic abundances of heavy elements, relative to solar values, derived to date for χ Lupi and for six cool S stars (Wallerstein 1984).

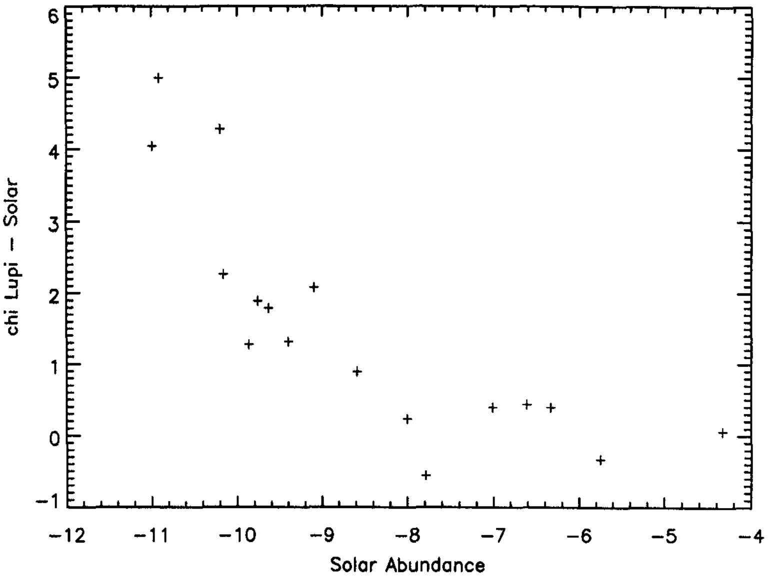

Figure 8. Logarithmic abundances of heavy elements, relative to solar abundances, for χ Lupi, versus the solar abundances.

abundances of many of these elements in young, "normal" stars or in the current interstellar medium. Presumably, the latter would more accurately represent the pre-stellar material from which the A_p and B_p stars formed.

Cardelli, Savage and Ebbets (1991, and private communication) have used the GHRS to obtain spectra of the interstellar medium with unprecedented resolution and S/N ratio. For the first time they have begun to detect trace elements in the ISM, such as Copper, Gallium, Germanium and Krypton. Cu, Ga and Kr exhibit the underabundances commonly attributed to depletion of interstellar gas-phase material due to adsorption onto grains. However, the first analyses of Germanium produced an unexpected result. In spite of possible depletion, Germanium appeared to be 0.2 to 0.6 dex OVERABUNDANT in the ISM relative to the sun. If one makes a plausible correction of a few tenths of a dex to account for depletion, then the ISM Germanium abundance would approach the +0.9 dex overabundance relative to the sun that we see in χ Lupi.

This striking result seemed to provide the first shred of evidence that the material from which young stars have formed in our galaxy may have been enriched, at least in certain elements, by the ongoing processes of stellar evolution and interstellar replenishment over the past 4.5 billion years. Unfortunately, Savage (1992, private communication) has now found it to be spurious. The ISM Germanium abundance was derived from GHRS observations of the λ1237.06 (UV4) line of Ge II. The transition probability of this line is mis-stated (by a factor of 10) in Morton (1991), leading to derived ISM Germanium abundances which were an order of magnitude too large.

Our attempts to explain the apparent magnitudes of abundance anomalies in chemically peculiar stars must take into account our uncertain knowledge of the correct "starting values" for these abundances in the pre-stellar material. It is evident that we will have to rely entirely on abundances of trace elements derived from apparently "normal," young stars to gain insight into the compositional evolution of galactic material since the birth of the sun.

REFERENCES

Adelman, S.J. 1988, MNRAS, 235, 749

Adelman, S.J., Wahlgren, G.M., & Robinson, R.D. 1992, in preparation

Anders, E., & Grevesse, N. 1989, Geochim.Cosmochim.Acta, 53, 197

Bengtsson, G.J., Berzinsh, U., Larsson, J., & Svanberg, S. 1992, A&A, in press

Cardelli, J.A., Savage, B.D., & Ebbets, D.C. 1991, ApJ, 383, L23

Dworetsky, M.M. 1971, Ph.D. Thesis, University of California at Los Angeles

_______., 1972, PASP, 84, 254

Dworetsky, M.M., & Vaughan, A.H., Jr. 1973, ApJ, 181, 811

Dworetsky, M.M., Storey, P.J., & Jacobs, J.M. 1984, Phys.Scripta, T8, 39

Joueizadeh, A. 1992, in 4th International Colloquium On Atomic Spectra And Oscillator Strengths For Astrophysical And Laboratory Plasmas, NIST, in preparation

Kono, A., & Hattori, S. 1982, JOSA, 72, 601

Kurucz, R.L. in Stellar Atmospheres: Beyond Classical Models, ed. L. Crivellari, et al. (Dordrecht: Kluwer), 441

Kurucz, R.L., & Peytremann, E. 1975, SAO Special Rpt. No. 390

Leckrone, D.S., Johansson, Se., Kurucz, R.L., & Adelman, S.J. 1990, in Atomic Spectra And Oscillator Strengths For Astrophysics And Fusion Research, ed. J.E. Hansen (Amsterdam: North Holland), 3

Leckrone, D.S., Johansson, Se., & Wahlgren, G.M. 1991, in HST Workshop: The Year Of First Light, ed. A.L. Kinney & J.C. Blades (Baltimore: Space Telescope Science Institute), 83

Leckrone, D.S., Wahlgren, G.M., & Johansson, Se. 1991, ApJ, 377, L37

Michaud, G., Reeves, H., & Charland, Y. 1974, A&A, 37, 313

Morton, D.C. 1991, ApJS, 77, 119

Sansonetti, C.J., & Reader, J. 1992, submitted to Phys.Rev.A

Shenstone, A.G., & Meggers, W.F. 1958, J.Res.Nat.Bur.Stds., 61, 373

Truran, J.W. 1991, in Evolution Of Stars: The Photospheric Abundance Connection, ed. G.Michaud & A. Tutukov (Dordrecht: Kluwer), 13

Wallerstein, G. 1984, JOSA B, 1, 307

White, R.E., Vaughan, A.H., Jr., Preston, G.W., & Swings, J.P. 1976, ApJ, 204, 131