

New Initiatives on RR Lyrae Chemical Compositions

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Abstract

The serendipitous discovery by Preston and colleagues of the neutron-capture-enhanced RR Lyrae variable star TY Gru (a.k.a. CS 22881-071 in the “HK” survey of very metal-poor halo stars) has resulted in a growing set of initiatives on the chemical compositions of RR Lyrae stars and their application to broader topics in Galactic halo structure. Here we summarize the main aspects of our work on TY Gru, including a new discussion of our search for possible orbital motion of this star around a putative unseen companion. Then we describe a few of the results of a newly-completed intensive spectroscopic investigation of 10 additional field RR Lyr stars. We finish by outlining current projects that seek to contrast the atmospheres and chemical compositions of RRc stars with those of the RRab stars, and that employ a much larger RRab sample in a chemo-dynamical study of Galactic halo RR Lyr.

1. Introduction

In 2005, the first author of this paper was contentedly continuing his investigations into the the contents of neutron-capture elements in very metal-poor stars (e.g., Sneden et al. 2003; Lawler et al. 2004). At the same time, the second author was beginning graduate study, hoping to expand on her initial research into pulsating subdwarf B stars (e.g., For et al. 2006). Neither one paid much attention to clear signals that the third author was re-kindling his interest in the research that had dominated his early career (e.g., Preston 1959): RR Lyr variable stars. But a special project a few years ago on the peculiar chemical composition of a single, accidentally-rediscovered

very metal-poor RR Lyr has expanded into a large-scale general investigation on the chemistry of the Galactic RR Lyr population. In this effort, the first two authors have been the happy recipients of the data acquisition, the spectrum analyses, the variable star insights, and the overall enthusiasm for this work by the third author.

In this contribution we first will review the unusual chemical composition of TY Gru, the star that started us down this research path. As part of the TY Gru discussion we will comment on our continued failure to detect orbital motion of TY Gru around an AGB relic presumed to be the origin of its abundance anomalies. Then we will describe the recently-completed detailed investigation into the atmospheric parameters and abundances of a sample of 10 intensively-observed RRab stars. Finally, we will sketch new initiatives that we are pursuing in contrasting the spectra of RRc with RRab variables, and in utilizing a much larger sample of RRab spectra gathered for the Galactic structure studies by Juna Kollmeier and her colleagues.

2. Neutron-Capture Elements in TY Gruis

A high-resolution spectroscopic survey (Preston et al. 2006a) of metal-poor Red Horizontal Branch (RHB) stars discovered in the HK survey (Beers, Preston, & Shectman 1992) included the star CS 22881-071. Velocity shifts in the two initial observations of this star quickly led to recognition that it was the previously identified RRab variable star TY Gru. This star was severed from the general RHB survey, and its subsequent analysis was published in a separate study (Preston et al. 2006b).

We became interested in TY Gru after noticing that several features of neutron-capture elements (n -capture, $Z > 30$) were anomalously strong compared to RHB stars with similar atmospheric parameters. In Figure 1 we show a small spectral region in the blue of TY Gru and some comparison stars. A practiced eye can see the main spectroscopic results without any detailed analysis: [1] all of the n -capture features are enhanced compared to those of an ordinary warm RHB star like CS 22186-005; [2] the relative strengths of the Ba II and La II lines in TY Gru are larger than those of Eu II; [3] the TY Gru n -capture line strength pattern is consistent with that of CS 29497-030, which exhibits products of slow n -capture synthesis (the s -process) but is incompatible with that of CS 22886-043, which has a distinct abundance signature of rapid n -capture synthesis (the r -process).

Our detailed abundance analysis, involving 10 elements representing all observable atomic n -capture mass/number domains, demonstrated that the TY Gru pattern is a near-perfect match to the abundance patterns of other very metal-poor, s -process-rich stars. We illustrate this agreement in Figure 2. While the overall amount of n -capture abundance excess is less in TY Gru than in CS 29497-030 (Ivans et al. 2005) and CS 31062-050 (Johnson & Bolte 2004), the agreement in abundance distribution would be near-perfect if the TY Gru numbers were to be renormalized to match, say, the Ba or La abundances of one of the comparison stars. In this figure, note especially the large

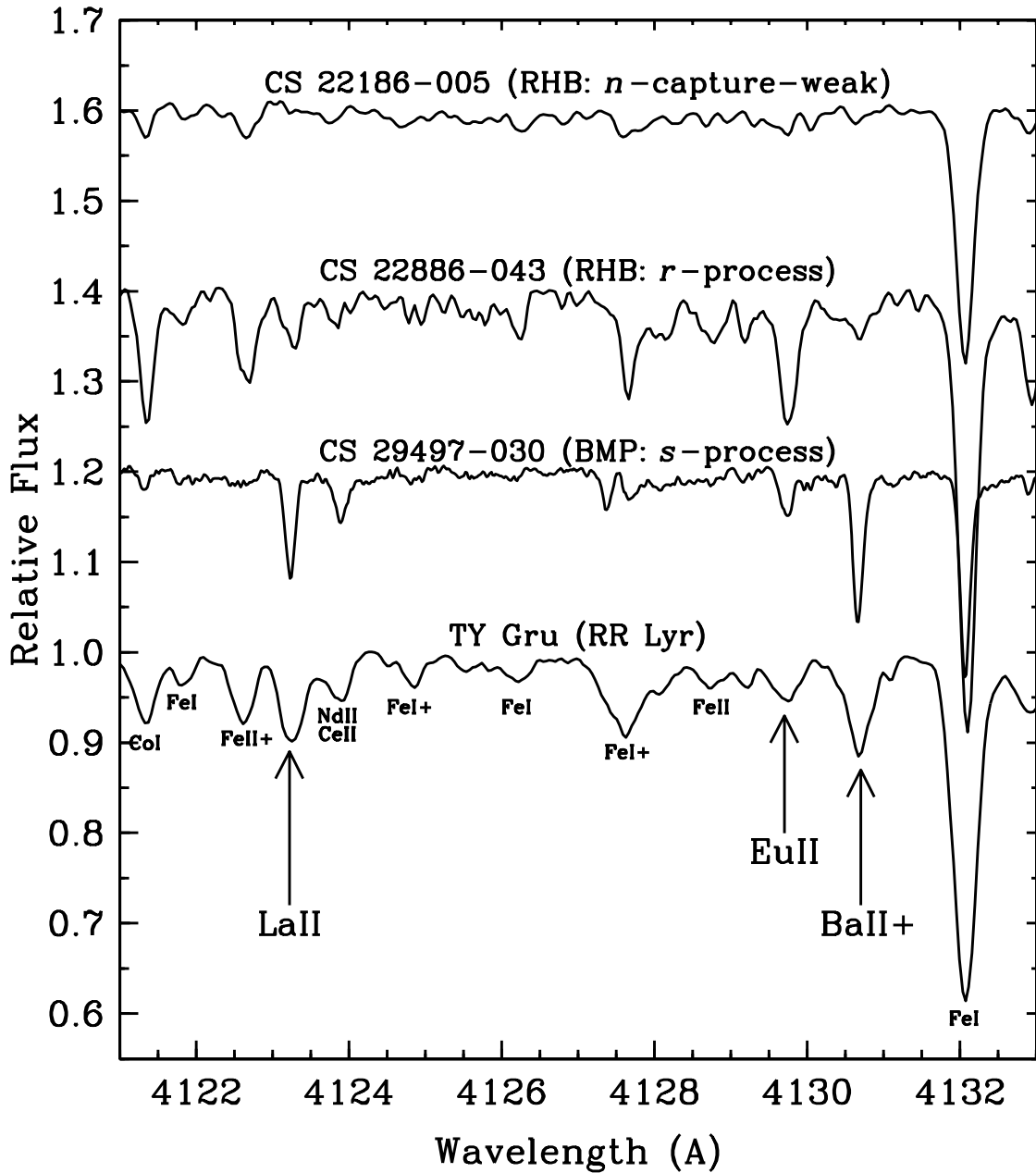


Figure 1.— Figure 1 of Preston et al. 2006b: spectra of four warm metal-poor stars in the region of the *n*-capture transitions La II 4123 Å, Eu II 4129 Å, and Ba II 4130 Å. The top spectrum is the RHB star CS 22186-005 (Preston et al. 2006a), which has no enhancements of *n*-capture elements. The second spectrum is the RHB star CS 22886-043 (Preston et al. 2006a), which has an *r*-process mix of *n*-capture enhancements (e.g., $[\text{Eu}/\text{Fe}] = +0.8$, $[\text{Eu}/\text{Ba}] = +0.6$). The third spectrum is the main-sequence blue metal-poor star CS 29497-030 (Ivans et al. 2005), which has an *s*-process set of *n*-capture overabundances (e.g., $[\text{Eu}/\text{Fe}] = +2.0$, $[\text{Eu}/\text{Ba}] = -0.3$). The bottom spectrum is that of TY Gru.

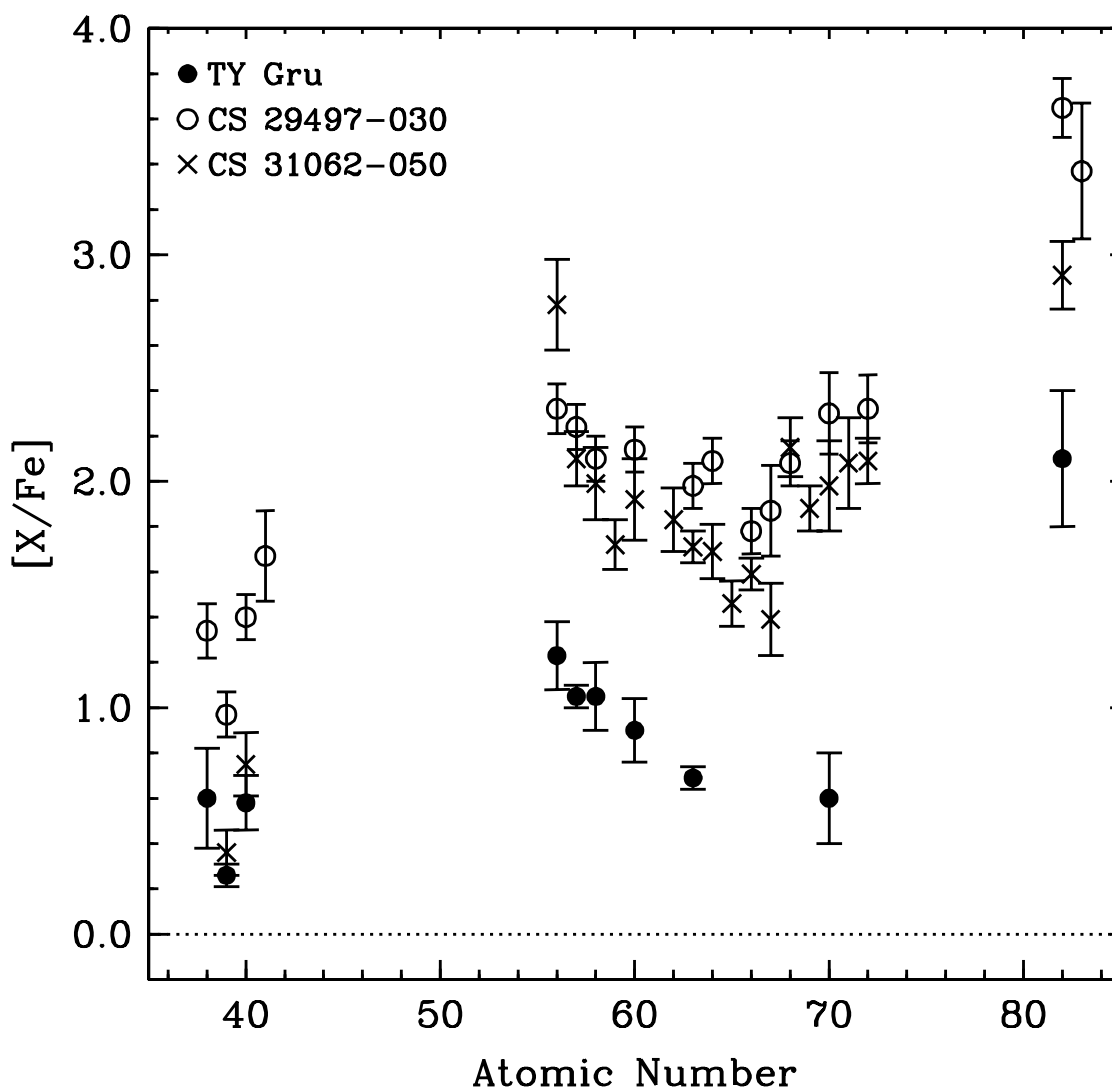


Figure 2.— Figure 9 of Preston et al. 2006b: relative abundance ratios of n -capture elements in TY Gru and in Pb-rich metal-poor stars CS 31062-050 (Johnson & Bolte 2004) and CS 29497-030 (Ivans et al. 2005). The solar abundance ratio $[X/Fe] = 0$ is denoted by a dotted line.

overabundances of all n -capture elements ($+0.3 \lesssim [\text{element}/\text{Fe}] \lesssim +2.1$); the decline in relative overabundances among the rare-earth elements as atomic number increases from $Z = 56$ to 70; and finally the enormous overabundance of Pb, the penultimate stable element. Preston et al. (2006b) also derived large carbon overabundances in TY Gru. These are all unmistakable signatures of s -process synthesis in low-metallicity He-fusion zones of highly evolved (AGB) stars (e.g., Gallino et al. 1998; Goriely & Mowlavi 2001).

The TY Gru investigation featured an observational/analytical advance in RR Lyr spectroscopy which has proven to be important in our recent work. Much of the previous RR Lyr abundance work (e.g., Clementini et al. 1995; Lambert et al. 1996)

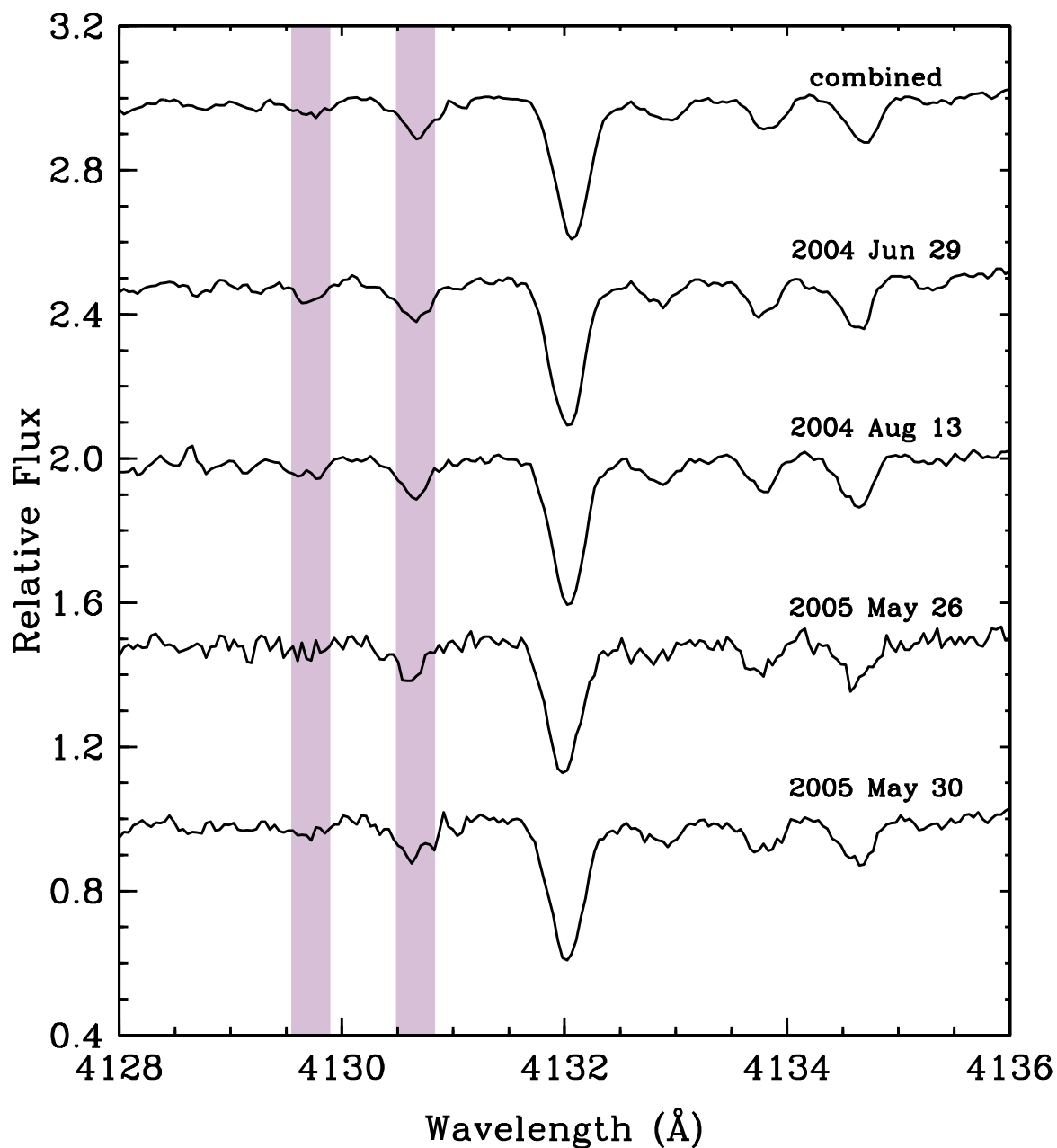


Figure 3.— Adapted from Figure 6 of Preston et al. 2006b: individual spectra of TY Gru taken at phase $\langle \phi \rangle = +0.78$, and the mean “combined” spectrum (at the top of the figure). We have added here vertical gray bars to indicate the positions of the Eu II transition at 4129.7 Å and the combined Ba II+Eu II feature at 4130.6 Å. While the individual spectra give little confidence in detection of the Eu II line, it is clearly visible in the combined spectrum.

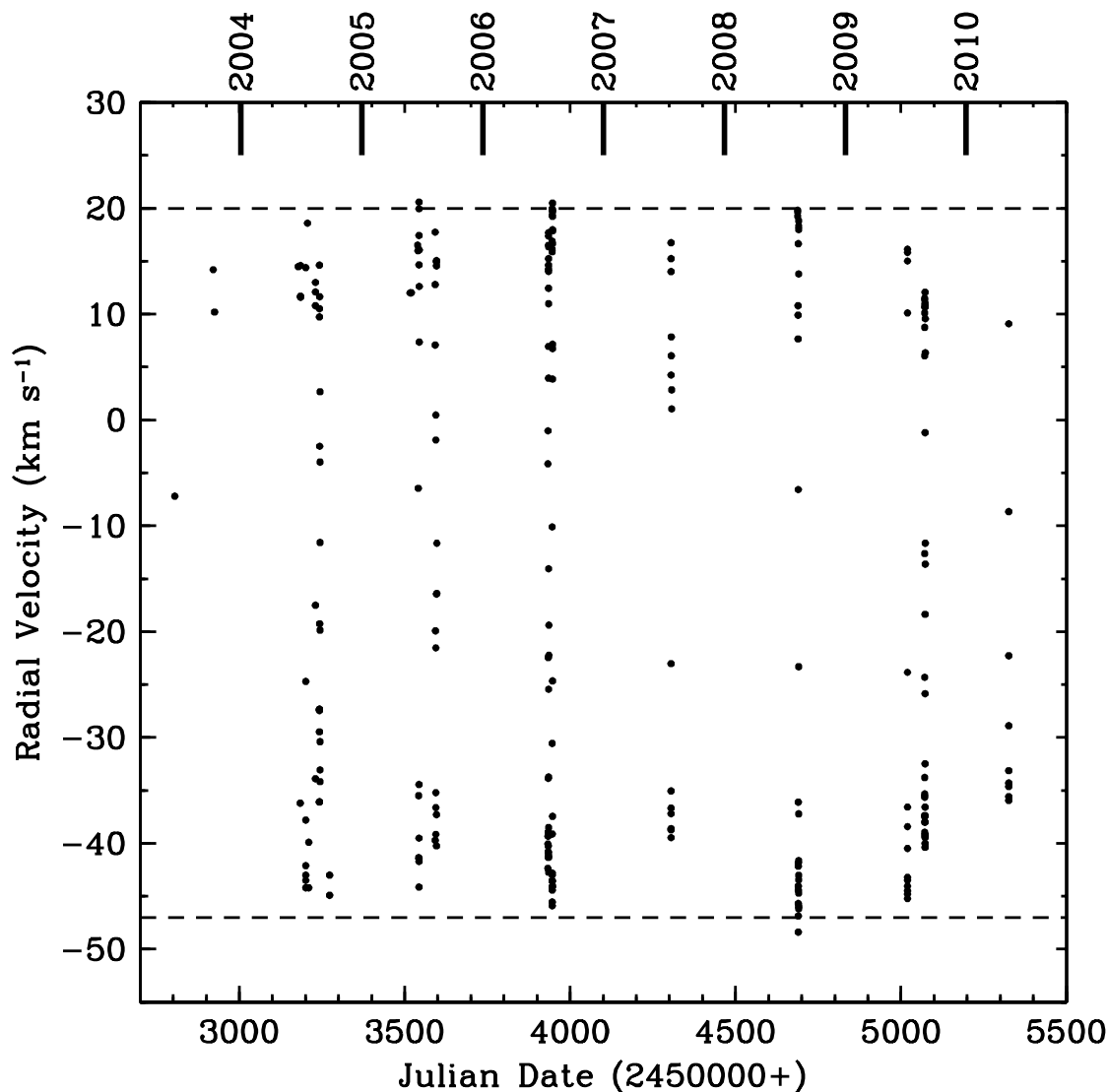


Figure 4.— Radial velocities extracted from individual spectra of TY Gru obtained from 2003 through 2010. The data are shown as a function of Julian date, but to assist the reader we have drawn vertical lines at the top of the figure to denote January 1 of the year that is written at the top. Horizontal lines have been drawn to mark the radial velocity envelope limits for TY Gru.

was relatively photon-starved and consequently employed few spectra. These data were generally obtained at one mean phase position with substantial phase smearing. Thanks to the availability of substantial amounts of time on large telescopes equipped with efficient echelle spectrographs, Preston et al. (2006b) were able to obtain 82 high-resolution spectra in maximum integration times of about 15 minutes, which correspond to a pulsational phase interval of $\Delta\phi = 0.02$. This procedure produced individual spectra of relatively low signal-to-noise (S/N), but the repeatability of RR Lyr spectroscopic variations allowed us to improve S/N by addition several spectra

obtained at similar phases, as we illustrate in Figure 3. The phase for the TY Gru abundance analysis, $\phi \sim 0.8$, was chosen to be near light minimum in the belief that this would be the optimal phase (most stable photospheric conditions). Although this had been a popular choice in past RR Lyr studies, our subsequent work has forced a re-evaluation; see §3.

TY Gru is the first RR Lyr star to be found with large carbon and *s*-process abundance enhancements. Nearly all metal-poor stars with these abundance characteristics are proven or suspected members of binary star systems with unseen secondary companions (e.g., McClure 1997; Preston & Sneden 2001; Lucatello et al. 2005). This is the simplest explanation for the TY Gru abundances, but observational proof of the idea has been difficult to obtain.

Preston et al. (2006b) were unable to detect any secular drift in the the TY Gru systemic radial velocities that might be indicative of wide-binary orbital motion. At that time however only two years of spectra contributed to the radial velocity information. In subsequent years more spectra have been gathered, and Preston’s (2011) Figure 1 displays the expanded velocity set. Even more recent TY Gru spectra leads to one more update which we show in Figure 4. TY Gru is a Blazhko star which exhibits a modest variation of radial velocity amplitude in a period of about 68 days as illustrated in Figures 10 and 11 of Preston et al. (2006b). The Blazhko phenomenon produces a change in velocity amplitude but not in the systemic velocity. In Figure 4 we see such amplitude variations, but the minimum and maximum radial velocities in each observing season lie within the dashed horizontal lines in the figure; they do not appear to have shifted up or down during the past seven years.

This lack of secular velocity drift for TY Gru can be used to place a constraint on the period of orbital motion. We adopt a mass for TY Gru of $M = 0.68M_{\odot}$, a typical value for RR Lyr stars (Castellani, Castellani, & Cassisi 2005), and assume a mass for a putative white-dwarf companion of $M \approx 0.6M_{\odot}$. From the observed dispersions in upper and lower bounds of the radial velocities shown in Figure 4 we believe that we could detect a change in systemic velocity of 5 km s^{-1} during the past 2000 days (half orbital period) had it occurred. The circular velocities for our adopted masses and orbital periods of 4000 and 8000 days are 6.8 km s^{-1} and 5.4 km s^{-1} , respectively. These periods bracket the longest orbital periods (5324 d and 6489 d) that have been found for marginally detectable Ba/CH giants (Boffin & Zacs 1994). From the above considerations we argue that the orbital period of the putative TY Gru binary must be substantially greater than 4000 d. There must be a longest period (largest binary separation) for which wind accretion from an AGB companion will fail to produce the observable pollution of the TY Gru envelope. Thus, the search for orbital motion of TY Gru has interesting astrophysical implications. We note, finally, that Preston & Sneden (2001), and Preston (2009b) have reported similar difficulty in the detection of orbital motion in several main sequence carbon stars.

3. An Intensive Spectroscopic Investigation of Field RRab Variables

A larger-scale investigation of RR Lyr was conceived in part to understand if possible binary mass transfer from a retired compact-star companion had created a unique evolutionary HB status for TY Gru (Preston 2011). A sample of 10 RRab stars with photometric properties similar to TY Gru were intensively observed with the Las Campanas du Pont telescope and its echelle spectrograph; extant spectra of TY Gru were added in. The resulting data set consists of over 2300 short-integration spectra, about 200 spectra/star, covering the spectral range $3500 \text{ \AA} < \lambda < 9000 \text{ \AA}$, with resolving power $R \sim 27,000$, and typical S/N of 20 in the blue. All phase intervals of all program stars have been sampled with multiple spectra.

This rich database can be mined to address a variety of questions about RR Lyr atmospheric physics, and already Preston (2009a) has discovered unexpected helium emission lines at some phases in all of the stars. We also have used these spectra to refine their velocity information and pulsational ephemerides (For, Preston, & Sneden 2011a).

Here we outline just a few aspects of our derivation of *photospheric* parameters T_{eff} , $\log g$, and ξ_t , overall [Fe/H] metallicities, and relative abundance ratios [X/Fe] for our RRab sample. Detailed results are described in For, Sneden, & Preston (2011b).

- Temperature, gravity, and microturbulence vary in similar and predictable ways throughout the pulsational cycles in all of our RRab sample. As one example, in Figure 5 we show the variations in these quantities in program star RV Oct. The phase-dependent atmospheric parameters are for a particular RRab variable, but pulsational phase changes are qualitatively always the same in our program stars (and most likely in all “normal” RRab stars as well).
- The optimal phase for abundance studies, defined as that phase at which the metal absorption lines are sharpest and most symmetric, occurs at $\phi \sim 0.35$, not at the minimum light phase of $\phi \sim 0.75$. Future RR Lyr chemical composition studies should concentrate on $\phi \sim 0.35$ if possible.
- In spite of T_{eff} changes of more than 1000 K and $\log g$ changes of more than 1 dex during each pulsational cycle, the [Fe/H] metallicities displayed in Figure 6 appear to be essentially invariant to within the uncertainties of an individual abundance determination, over the entire RV Oct pulsational cycle. This statement can be applied to our whole sample of RRab stars, suggesting that reliable metallicities can be determined at any RR Lyr phase, as long as good estimates of T_{eff} , $\log g$, and ξ_t can also be extracted from the spectra.
- Just as importantly, nearly all derived relative abundance ratios are insensitive to pulsational phase, and are mostly in accord with expectations based on abundance ratios for other halo-star evolutionary groups. In Figure 6 we show variations of

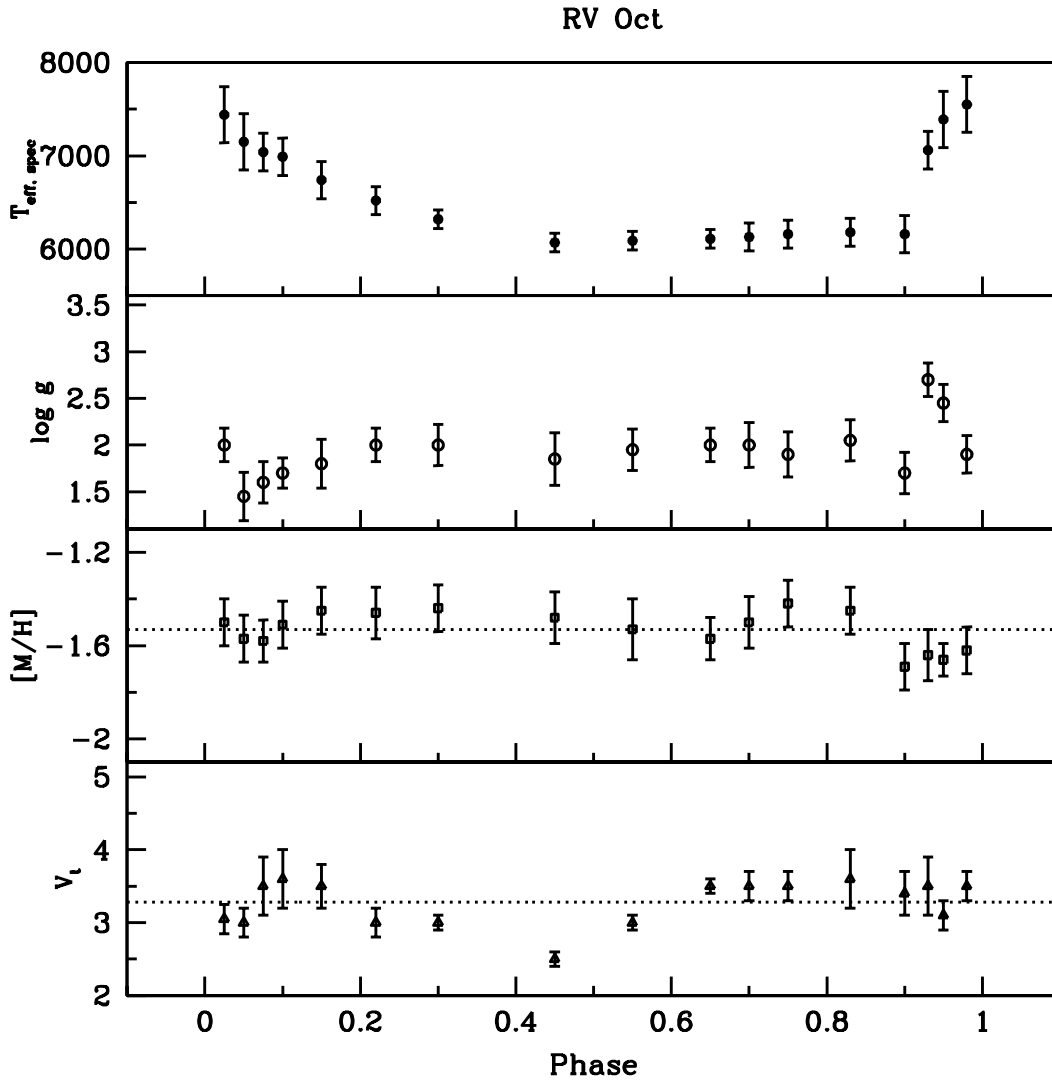


Figure 5.— Variations in atmospheric parameters with pulsational phase for RV Oct. The >200 individual spectra for this star have been binned into 17 phase intervals to increase S/N .

eight light-element abundance ratios, and one can easily divide the confidence levels of claimed phase invariance into excellent (Ca I, Sc II, Ti I), probable (Na I, Mg I), uneasy (Si I, Si II) and unproven (Al I).

- The elements Si and Ca are official members of the light α -element group, whose major isotopes are multiples of helium nuclei. Element Ti has a courtesy membership in the α group, because while its major isotope ^{48}Ti is not an aggregate of α particles, its abundance in most metal-poor stars mimics those of the true α elements. We find the abundance ratios $[\text{Mg}, \text{Si}, \text{Ca}, \text{or Ti}/\text{Fe}] \sim +0.5$, in qualitative agreement with the elevated α abundances seen in other types of metal-poor

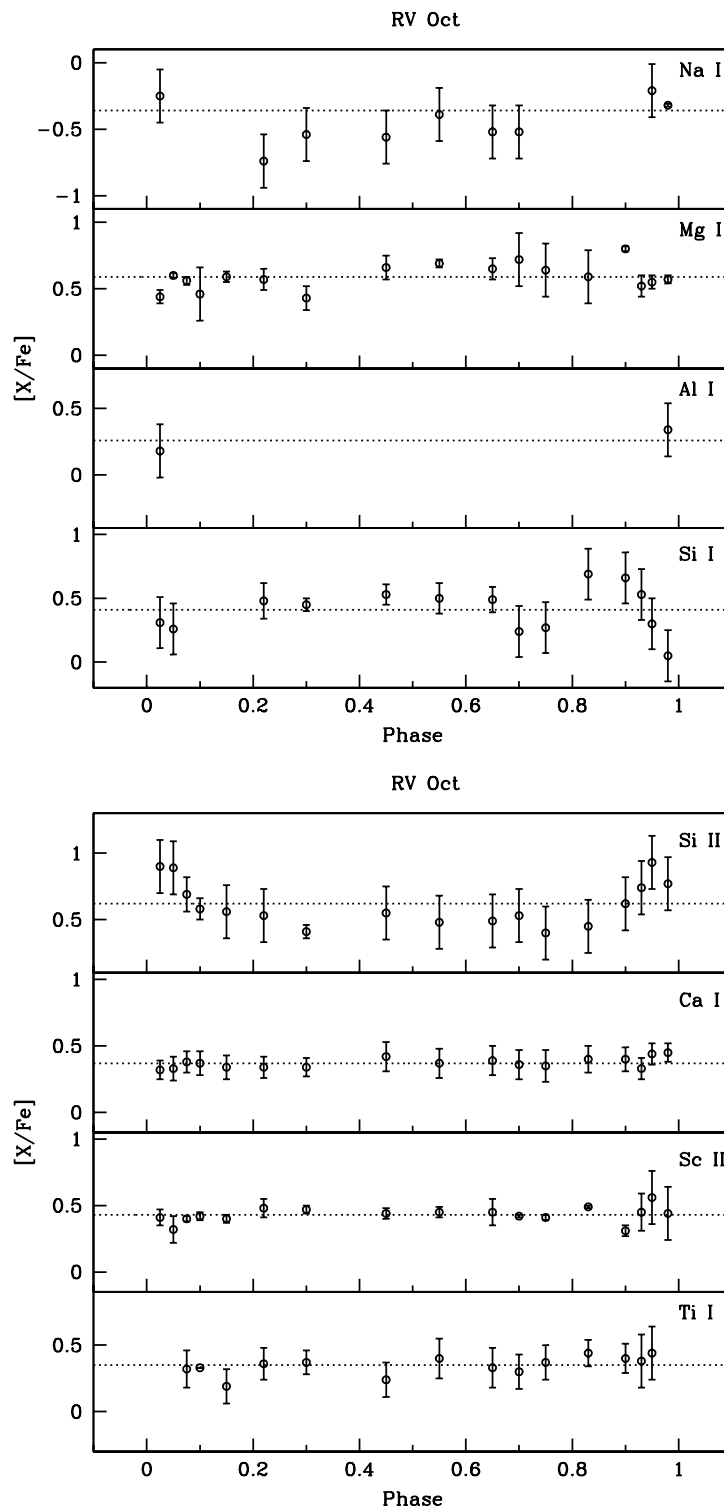


Figure 6.— Variations of the relative abundances of some light elements in RV Oct.

stars (e.g., Cayrel et al. 2004).

- Si abundances based on Si I lines in the blue spectral region are known to be temperature-sensitive (e.g., Preston et al. 2006a, Sneden & Lawler 2008). As one can see in Figure 6, the addition of Si II lines in RV Oct does little to alter the situation. Happily however, on average both species support the notion of Si overabundance in this and in the rest of our RRab sample.

These comments only touch on the some of the For et al. (2011b) results. Please see that paper for extended comments on the above points, and for discussion of the relative abundances of heavier elements, the variation of microturbulent velocity with pulsational phase, the relationship between ξ_t and line full-width-half-maxima, and a new method to estimate RRab effective temperatures without extended analyses.

4. Some Current Projects

Most previous spectroscopic studies of horizontal-branch variables have focused on the RRab stars, the majority component of the RR Lyr population. Much less attention has been paid to the RRc stars. The RRc stars present some observational challenges. They are relatively rare (hence fainter on average), and they are hotter so their absorption lines are weaker at constant abundance.

We have begun a program to derive atmospheric parameters and elemental abundance ratios in a sample of field RRc variables. We employ the same du Pont echelle configuration that was used to obtain the RRab spectra described above. In spite of the faintness of the targets we have obtained satisfactory data by co-adding individual spectra taken at similar phases. In Figure 7 we present a small spectral region in one of the RRc target stars. Obviously the spectra of this star and a comparison RRab shown in this figure are not as good as that of an RHB star studied by Preston et al. (2006a); the smaller telescope and shorter spectroscopic exposure times result in lower S/N. However, one can clearly see all the major absorption features in the RRc spectra that are necessary to determine both overall metallicity and enough abundance ratios to be able to describe the chemical history of the RRc stars. Note also from comparison of the top and middle spectra in Figure 7 that the FWHM (macroturbulence) of the RRc absorption lines is lower than that of the RRab star.

Analysis of the RRc spectra are underway. We have obtained preliminary estimates of the atmospheric parameters of one of the stars. To accomplish this, we began with the same Fe input line list that was used by For et al. (2011b), then measured equivalent widths, and performed a standard atmospheric analysis. In Figure 8 we show the abundances of individual Fe I lines as functions of excitation energy, line strength, and wavelength. Not shown in this figure are the abundances from Fe II lines. The derived model satisfied the usual spectroscopic criteria of no substantial trends of Fe I abundances with excitation potential, equivalent width, and wavelength, along

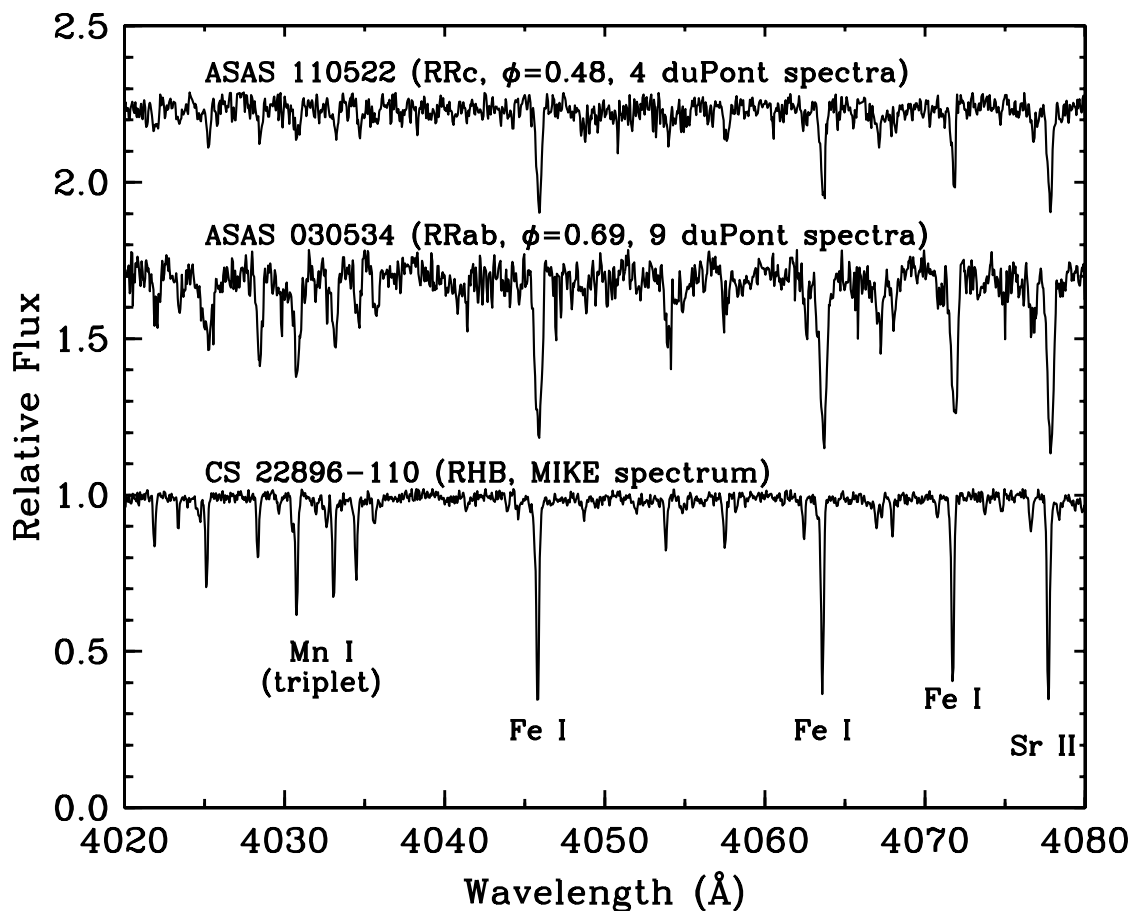


Figure 7.— Example spectra of an RRc variable (top), an RRab (middle) and a non-variable red horizontal-branch star (bottom). The single RHB spectrum was obtained with a larger telescope (Magellan) at high spectral resolution ($R \sim 45,000$) and with a long exposure time, while the spectra of the RR Lyr stars were gathered with the smaller du Pont telescope, lower resolving power ($R \sim 27,000$), and very short exposure times. The number of RR Lyr individual spectra that were co-added, and the mean phases of the spectra, are indicated in the figure legend.

with equality of the mean Fe I and Fe II abundances. The temperatures and gravities are consistent with general expectations for RRc variables. The derived metallicity, $[\text{Fe}/\text{H}] \equiv \log \epsilon_{\text{star}} - \log \epsilon_{\text{Sun}} = 5.7 - 7.5 = -1.8$, clearly indicates membership of this star in the Galactic halo population. But most intriguingly, we derive $\xi_t \approx 2.1 \text{ km s}^{-1}$, much smaller than typical values of RRab stars ($3\text{--}4 \text{ km s}^{-1}$). This points to absence of shock-wave disturbances in RRc atmospheres at the microscopic level.

We also are participating in Juna Kollmeier’s statistical parallax program. A major spectroscopic survey has been undertaken by Kollmeier and her colleagues to derive radial velocities and abundances for more than 1000 RR Lyr stars. The principal goal of this project is to calibrate the fundamental distance scale using the RR Lyr as standard candles. The spectra being gathered for this project have relatively low S/N, of necessity. The spectra are more than adequate produce good radial velocities.

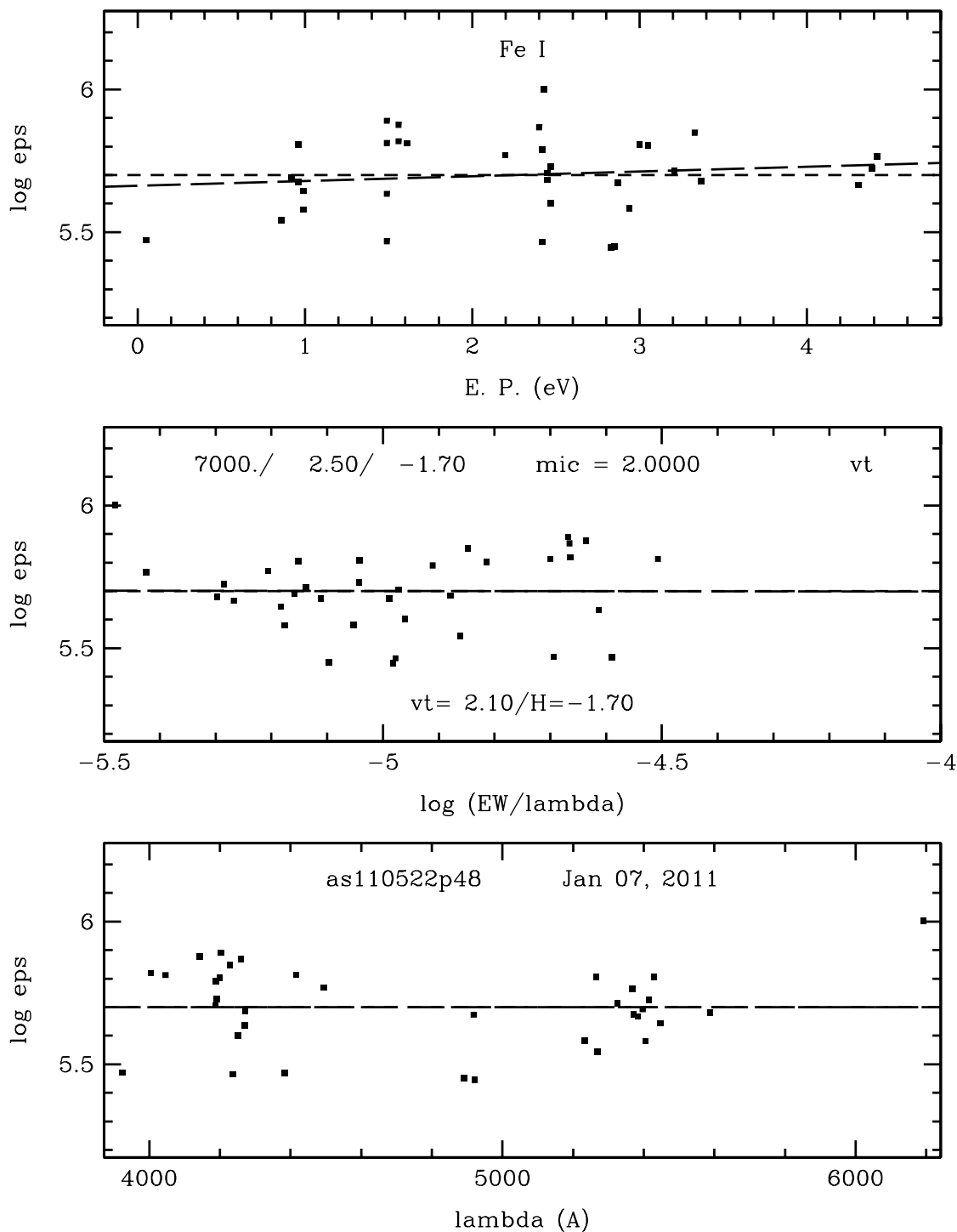


Figure 8.— Abundances of individual Fe I lines in the RRc star AS110522 at phase $\phi \approx 0.48$. The top panel has the run of these abundances with excitation potential, the middle panel with the log of the reduced width, and the bottom panel with wavelength.

Abundance determinations pose more of a challenge. Our part of the overall effort will be to derive metallicities and a limited set of abundance ratios. We are finding that that reliable metallicities can be obtained with spectra of very weak signal by using the “multiplex” advantage of the many Fe-group element absorption features that are present in RR Lyr stars. We are employing techniques that are similar to those pioneered by Carney et al. (1987). We are initially concentrating on the 5000–5400 Å spectral region (as did Carney et al.) which contains the Mg I b lines and other strong spectral features. For detailed abundance ratios other spectral domains will need to be surveyed (e.g., the 4500 Å region which contains Ba II 4554 Å). Observations for this program are underway.

5. Acknowledgments

We are grateful for support from the U.S. National Science Foundation over many years, currently with grant AST 0908978.

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