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The UV Spectra of Mira Variables: A View with *HST*

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Abstract:

We report on the first set of UV spectra taken of Mira stars under high dispersion with the Goddard High Resolution Spectrograph onboard the *Hubble Space Telescope*. Two spectral regions were observed, 2320 Å – 2368 Å to record the C II] (UV0.01) multiplet and 2785 Å – 2835 Å to obtain the Mg II h & k lines, for the Mira variable stars R Hya (phase 0.26) and R Leo (phase 0.12). The R Hya Mg II spectrum is very clean and shows overlying absorption from Fe I (UV3) and Mn I (UV1) over the k line. The fluoresced Fe I (UV44) feature at 2824 Å is plainly visible in this spectrum, whereas past *IUE* observations at high dispersion were unable to record this feature. Remarkably, the newly identified fluoresced Fe I (UV45) feature near 2807 Å is seen in this spectrum. Until now, this line has only been seen in cool carbon stars with *HST*/HRS. It is remarkable in that it is pumped by the thin C II] (UV0.01) emission line at 2325.5 Å in the carbon stars. This line is the likely pump in the oxygen-rich Miras in our sample as well. Two of the strongest C II] (UV0.01) near 2325 Å are plainly seen in our spectrum. This region of the spectrum, however, is dominated by the Si II] (UV0.01) line near 2335 Å, opposite to what is observed in the carbon stars and the non-Mira oxygen-rich red giant stars. Very weak Mg II lines are seen in the R Leo spectrum at phase 0.12. At this phase, these lines are typically absent in *IUE* spectra.

1. Introduction

Mira variable stars are pulsating asymptotic giant branch (AGB) stars that display strong emission features that vary over the pulsation cycle (Merrill 1940; Bidelman & Herbig 1958; Wood 1975; Willson 1976). The *IUE* spacecraft has shown that UV emission line variability also is correlated with pulsations (Brugel et al. 1987; Bookbinder, Brugel, & Brown 1989; Luttermoser 1996). Besides the more typical collisionally excited lines, Miras also show strong fluorescent lines at both visual and UV wavelengths (Bidelman & Herbig 1958; Luttermoser 1996). Fe I (42) at 4202 Å and 4308 Å, both pumped by the Mg II k line, are a good example of this fluorescence.

In an attempt to understand the variability and the spectra of these stars, astronomers have been modeling the atmospheres of these stars with a variety of techniques. Sophisticated hydrodynamic models have been generated for these stars (e.g., Drinkwater & Wood 1985; Bowen 1988; Fleischer, Gauger, & Sedlmayr 1992). Luttermoser & Bowen (1992) and Luttermoser, Bowen, & Willson (1997) have used the Bowen (1988) models to generate NLTE synthetic spectra.

The *IUE* archives contain an enormous amount of data concerning Mira variables. However, *IUE* did not have the sensitivity to reach the faint C II] (UV0.01) intersystem multiplet near 2325 Å under high dispersion. This multiplet is sensitive to the electron density of the gas emitting these photons. As such, we have used the Goddard High-Resolution Spectrograph (HRS) onboard the *Hubble Space Telescope* (*HST*) to record these features, along with the Mg II features near 2800 Å. This data will be a strong constraint to the atmospheric models that are now being generated for these stars.

2. Observations

Two basic types of emission lines exist in the spectra of Mira stars: *collisionally excited lines* (e.g., Mg II h & k) and *fluoresced lines* (e.g., Fe I (42) at 4202 Å and 4308 Å). One problem that has existed prior to *HST* was the inability of *IUE* to record the C II] (UV0.01) multiplet near 2325 Å. These lines are important since flux ratios of various lines in this multiplet give an accurate measure of electron density in the region of the atmosphere giving rise to these lines. We attempted to overcome this through the use of the HRS onboard *HST*. Prior to the servicing mission, we were able to obtain data of two different (but similar) Miras at two different phases: R Hya at phase 0.26 taken on 9 July 1996 with the G270M grating through the large aperture and R Leo at phase 0.12 taken on 14 January 1997 with the same telescope configuration.

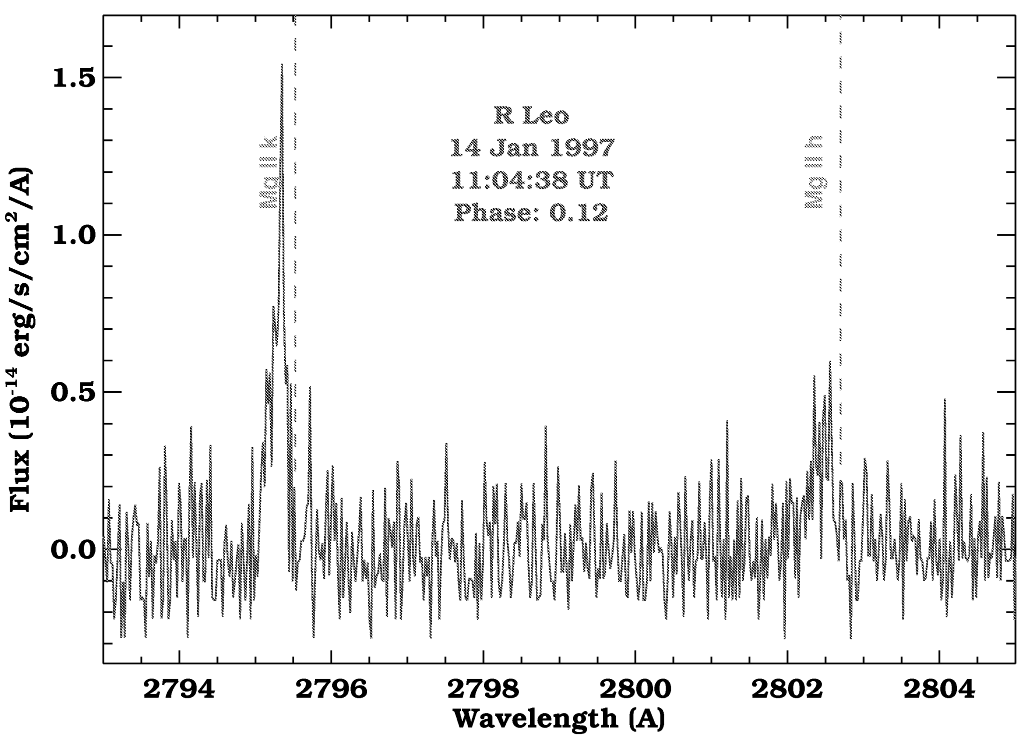

Figure 1. R Leo at phase 0.12 in the Mg II h & k region.

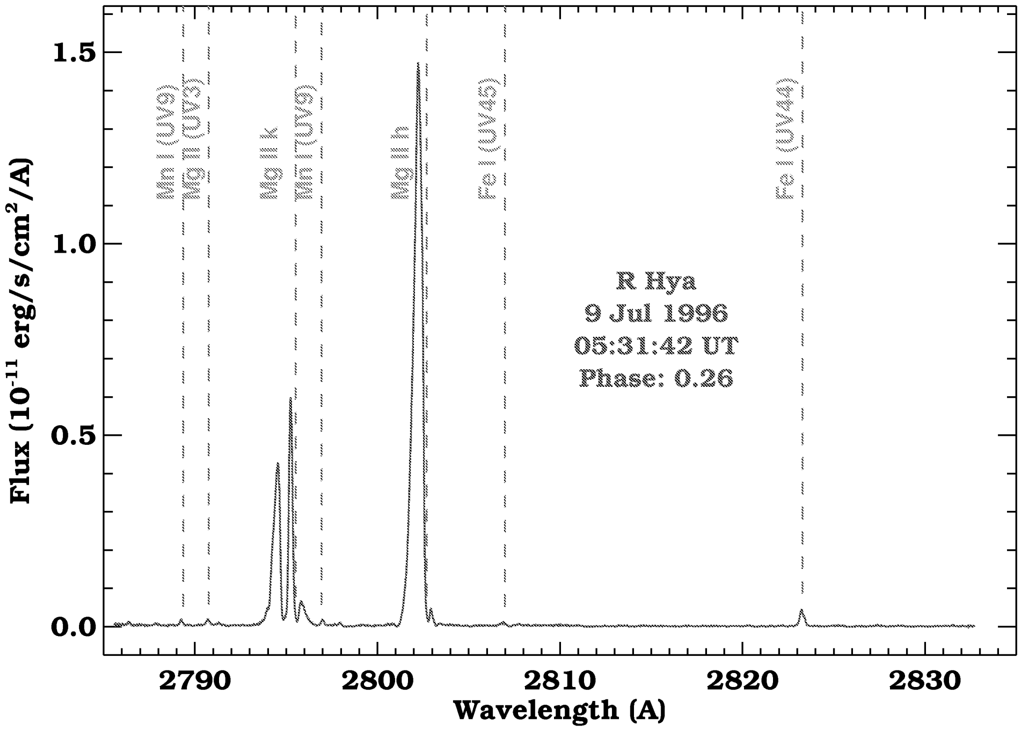

Figure 2. R Hya in the Mg II region at phase 0.26.

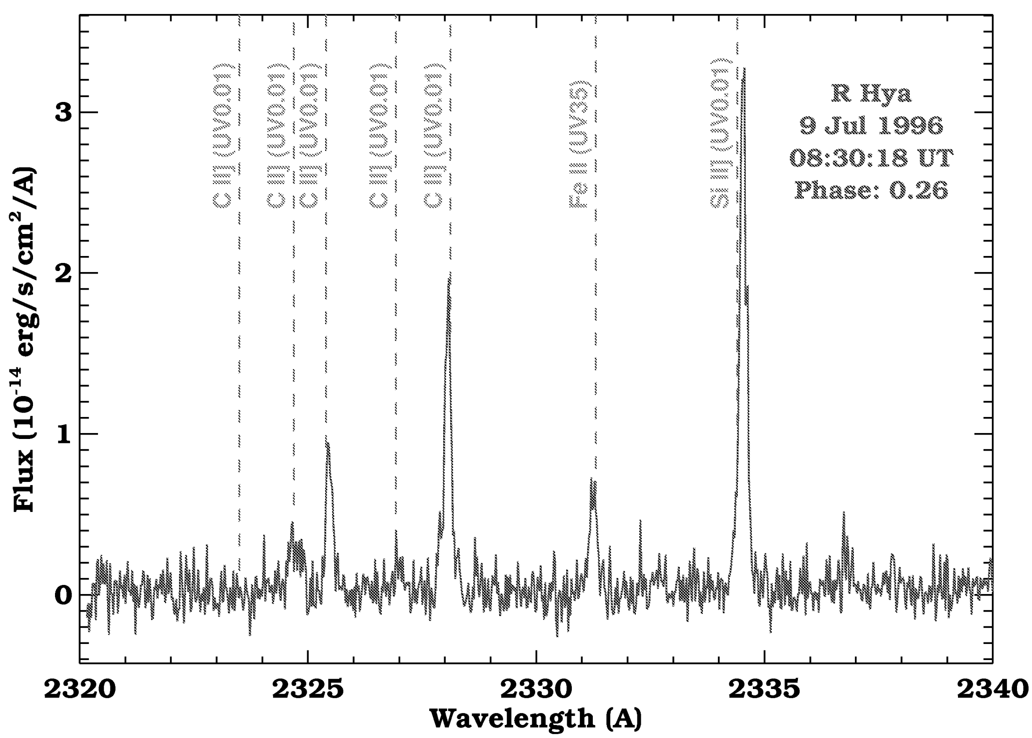

Figure 3. R Hya in the 2330 Å region at phase 0.26.

3. Results

At UV wavelengths (as observed with *IUE*), emission lines do not appear until phase 0.15 where they continue to gain strength in time until reaching a maximum around phase 0.3-0.4. Meanwhile the peak Balmer line flux at visual wavelengths occurs at phase 0 (which is defined to be the maximum visual brightness). Figure 1 shows the Mg II lines in the spectrum of R Leo at phase 0.12 – the lines are just starting to rise out of the noise. These lines vary in brightness over the pulsational period reaching maximum flux around phase 0.3-0.4. This *HST*/HRS spectrum is the earliest (in phase space) these lines have been seen. Note that the flux of the k line is approximately twice as great as the h, similar to that seen in warmer red giant stars. Later as these lines strengthen, h becomes stronger than k due to the interaction of the k line photons with the overlying circumstellar (CS) absorption lines. The C II] (UV0.01) lines are still too faint to be seen at this phase. Figure 2 shows Mg II and other features at phase 0.26 in R Hya. As was seen with *IUE*, the Mg II h & k lines are blueshifted with respect to the stellar rest frame (dashed lines). The fluoresced Fe I (UV45) line (pumped from C II] λ2325.4) is also blueshifted whereas the Fe I (UV44) line (pumped from Mg II k) is relatively stationary with respect to the star. Meanwhile, Figure 3 shows the C II] (UV0.01) lines at this same phase for R Hya. This is the *first* time the C II] (UV0.01) multiplet has been seen in a Mira variable. The flux ratio of lines in this multiplet can be used to measure electron density. Unfortunately, the usually strong line at 2325.4 Å is compromised by CS absorption from an Fe I (UV13) transition at 2325.3 Å. The weak flux of the lines at 2324.7 Å and 2326.9 Å suggests an electron density of $\sim 10^9$ cm^{-3}, however, the uncertainties are large ($\sim$ 30%).

One surprising feature has been seen in the spectrum of R Hya – the Fe I (UV45) emission line at 2806.984 Å (Figure 4). This fluoresced line was first discovered in the *HST*/HRS spectrum of the carbon star UU Aur (Johnson et al. 1995). This line is *pumped* by the thin C II] line at 2325.398 Å through an Fe I (UV13) transition at 2325.320 Å. This is the first time this fluoresced-emission feature has been seen in a non–carbon star! The appearance of this feature in oxygen-rich stars suggests that one only need an appreciable CS shell over a *chromosphere* or *shocked region* to produce this feature. Unfortunately, this fact prevents us from using this line to determine the electron density in these stars. Deeper observations with STIS will be required to retrieve this information from the fainter, *noncompromised* C II] lines at 2324.689 Å and 2326.930 Å. The emission feature just longward of the strong Fe I (UV2) absorption line in Figure 4 has been tentatively identified as Tc II (UV4). If this identification is valid, it is the first time this emission feature has been seen in a cool giant star. With the help of Carpenter, Wing, & Stencel (1985), we have identified some of the absorption features seen in the UV spectra of Miras. One of the stronger absorption features in Figure 4 is the OH (1,0) R_1 band near 2811 Å.

The Mg II h & k lines are one of the main driving forces behind the various fluorescent features that are seen at visual wavelengths of Miras. Figure 5 shows the position of neutral-metal lines that absorb Mg II photons which are then re-emitted at visual wavelengths. Overlying absorption from a CS shell (i.e., the extreme outer atmosphere of the star) severely mutilate the Mg II resonance

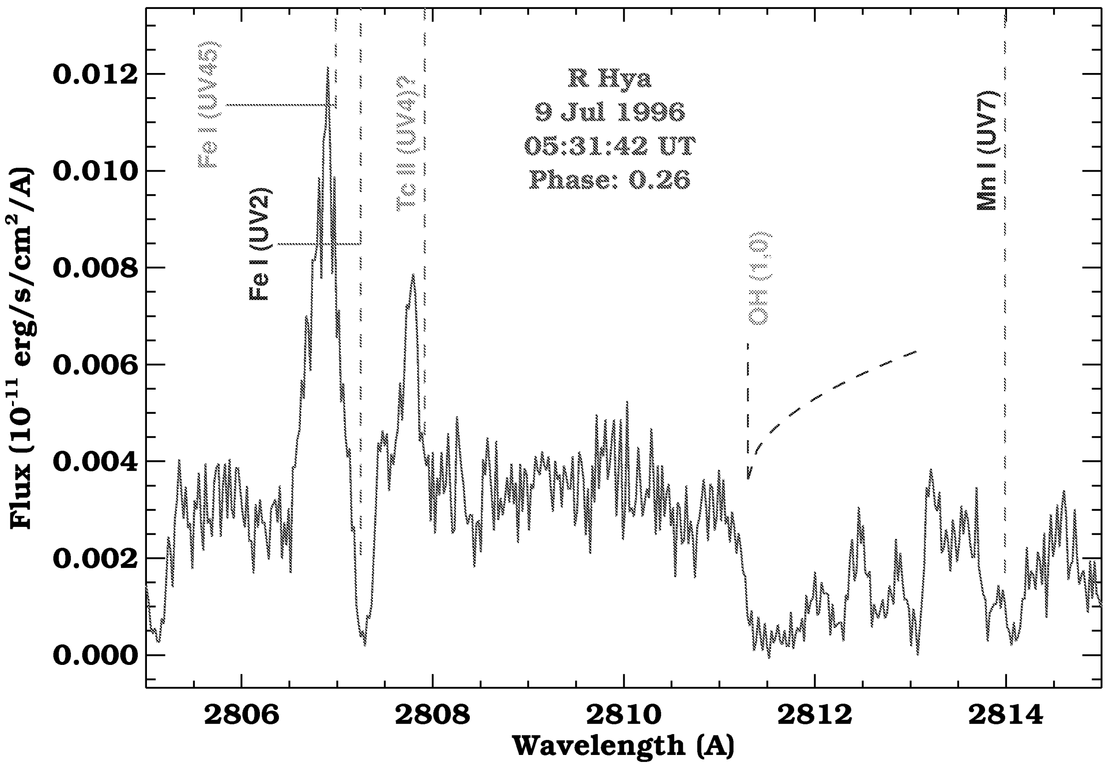

Figure 4. *HST*/HRS spectrum of R Hya showing the fluoresced Fe I (UV45) feature.

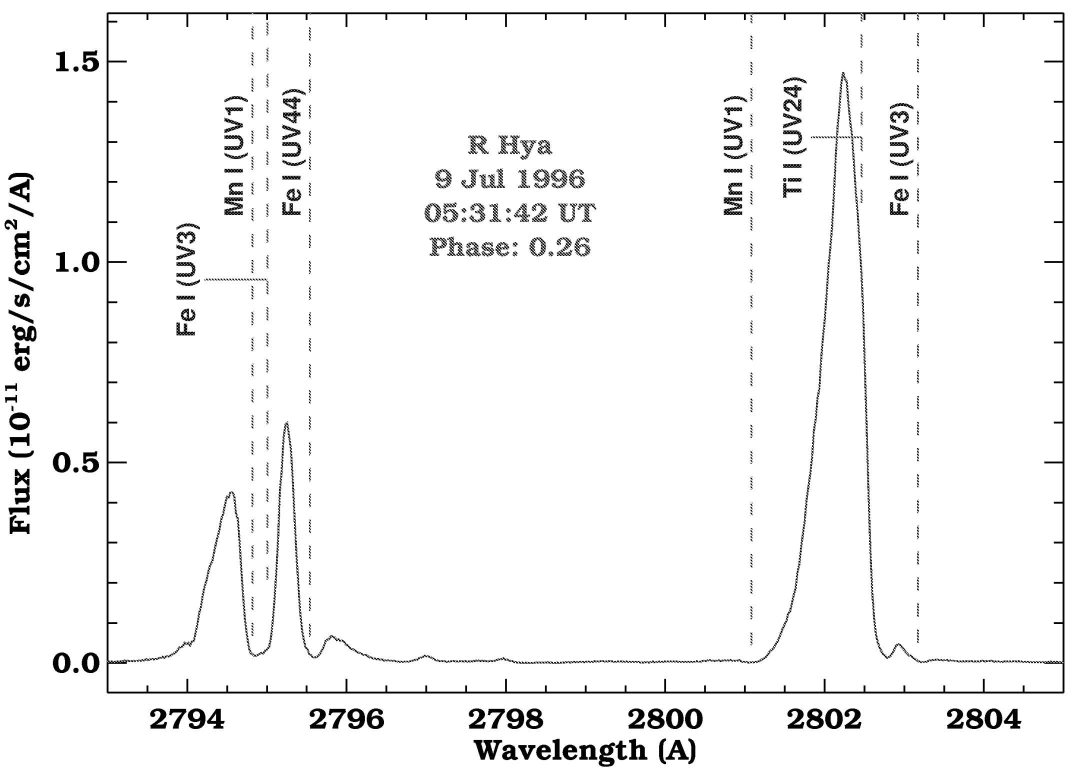

Figure 5. The location of strong CS absorbers in the vicinity of Mg II.

lines. In Mira stars, absorption from CS Fe I (UV3) gives rise to the strong fluorescent lines of Fe I (42) at 4202 Å and 4308 Å. The Mn I (UV1) resonance line at 2794.817 Å also produces fluoresced lines at visual wavelengths. A new fluoresced line at 4372.4 Å due to Ti I (277) is identified from ground-based spectra and its *pump* is identified here as Ti I (UV24) which absorbs Mg II h-line photons.

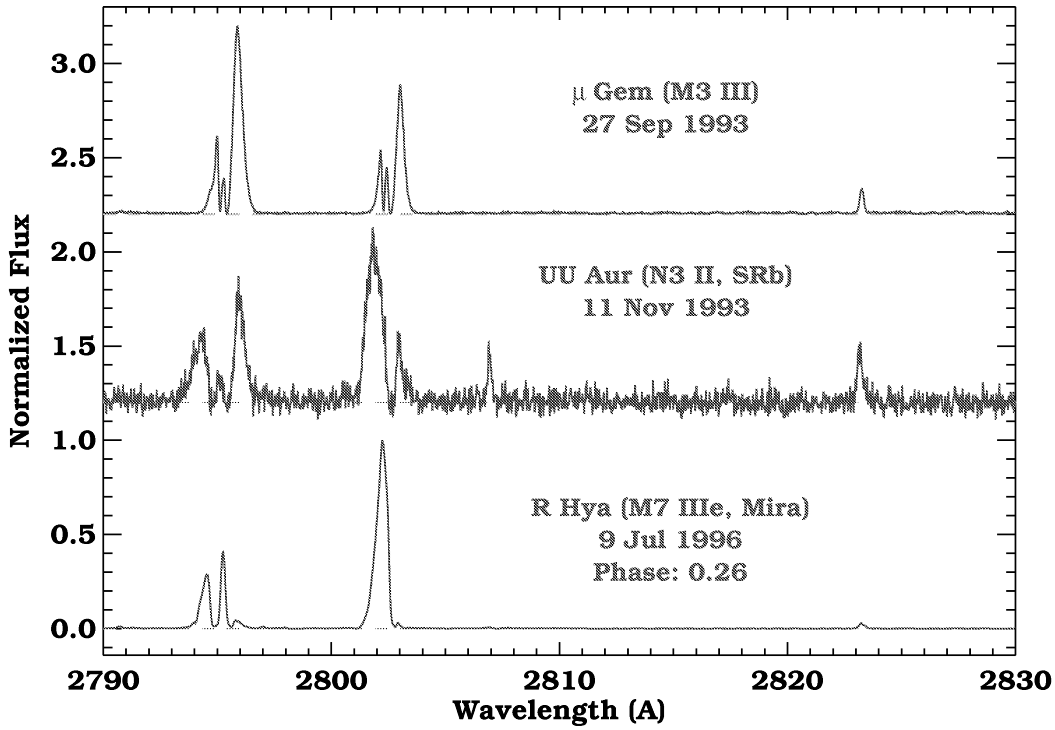

Figure 6. Mg II *HST*/HRS spectrum comparison for red giants.

It is interesting to note the differences and similarities in the UV emission lines for the various spectral and variability classes of red giant stars. Figures 6 and 7 show such comparisons. R Hya is an M7 Mira variable with an effective temperature of ~2200 K when at minimum light. For comparison, μ Gem is a nonvariable M3 red giant with an effective temperature of 3710 K, TX Psc is a carbon star of spectral class N0 with an effective temperature of 3030 K, and UU Aur is even a cooler carbon star (N3), with an effective temperature of 2825 K. Both of the carbon stars are semiregular (i.e., non-Mira) variable stars. In the Mira stars, the Mg II line emission is shifted blueward of the stellar rest velocity, whereas the semiregular, oxygen-rich variable stars and the nonvariable red giants display Mg II emission which is virtually at rest with respect to the stellar photosphere of the star. Also note that CS absorption is not evident in the earlier red giant star μ Gem (only interstellar absorption is seen). Indeed, in terms of UV spectra, the carbon-rich (non-Mira) giants appear more similar to the oxygen-rich Miras – Mg II k & h mutilation by overlying absorption and the appearance of the fluoresced Fe I (UV45) emission line in both spectra.

Meanwhile, the flux ratio of the C II] (UV0.01) lines indicate the electron density of the gas that gives rise to the emission. One can plainly see a clear difference between the oxygen-rich, non-Mira (μ Gem), the carbon-rich, non-

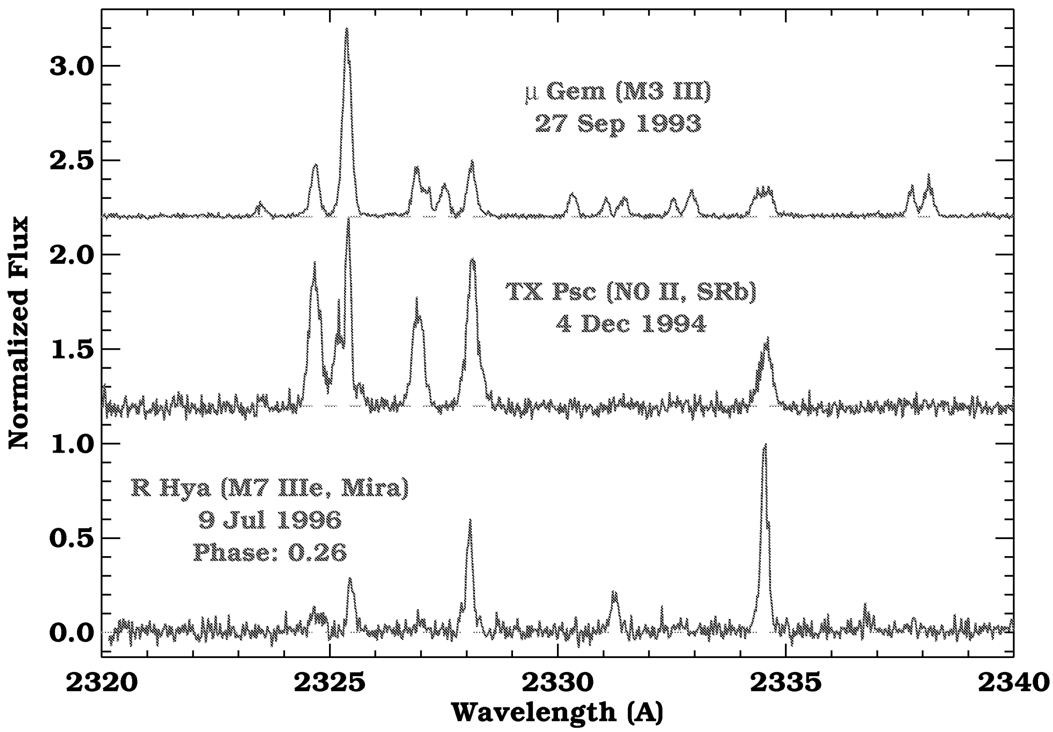

Figure 7. C II] and Si II] *HST*/HRS spectrum comparison for red giants.

Mira (TX Psc), and the oxygen-rich, Mira (R Hya). Although the uncertainties are high, the electron density in both TX Psc and R Hya are similar and a factor of two greater than the electron density in the C II] emission layers of the earlier M-star μ Gem.

4. Conclusion

We have observed the C II] (UV0.01) multiplet for the first time in Mira variables. Unlike the non-Mira variable red giants, the Si II] (UV0.01) multiplet is stronger than the C II] (UV0.01) multiplet. As was recently observed in the cool carbon stars, the Fe I (UV45) line is seen in fluorescence in Miras. Approximately 20% of the C II] flux goes into pumping this feature in carbon stars. However, 6 times the amount of flux in the C II] lines comes out in this Fe I line in Mira stars! This suggests that the CS shells around Mira stars are much thicker than they are around non-Mira carbon stars. The strength (in terms of FWHM) of the fluoresced Fe I (UV44) (pumped by Mg II) is similar in all of the stars in our sample. However the C II] lines are significantly thicker in the carbon star than the noncarbon stars. Indeed, these lines may not be *optically thin* in the carbon stars (see Carpenter, Robinson, & Johnson 1998 in this proceedings), no doubt due to the larger carbon abundances in these stars. The fluoresced Fe I (UV45) line is significantly thicker in the Mira star as compared to the carbon stars. Indeed, this is further proof that the CS shell around Miras are substantially thicker than the non-Mira carbon stars, even though both stellar types show the CS absorption over the Mg II lines. Finally, the Mg II lines control much of the fluorescence seen at visual wavelengths in Mira stars. A new fluorescent feature at 4372.4 Å is identified as Ti I (277) which is pumped by Mg II h via a Ti I (UV42) line.

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