THE CHROMOSPHERES OF CARBON STARS

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Abstract. Most oxygen-rich late-type giant stars show evidence for chromospheres in their visual spectra (e.g. Ca II H & K emission features). Cool (i.e. N–type) *non-Mira* carbon stars, however, have never been observed to have chromospheric emission in their Ca II H & K lines. However, faint Mg II h & k lines were detected in emission in low-dispersion IUE spectra of the brightest cool carbon stars in the early 1980s. May 1984 saw the first (and only) successful high-dispersion IUE spectrum taken of a cool carbon star, TX Psc (N0; C6,2). Armed with this high-dispersion spectrum, as well as low-dispersion IUE and ground-based spectra, Luttermoser et al. (1989) made the first detailed attempt to *semiempirically* model the chromosphere of a cool carbon star. This model was successful in reproducing the Mg II lines, but it was not well constrained due to the lack of other observed high-resolution chromospheric profiles for comparison. Modeling carbon star chromospheres can now be addressed more accurately with HST/GHRS high-resolution spectra. New fluoresced emission features have been discovered in the GHRS spectra of carbon stars that are not present in their oxygen-rich counterparts.

1. Introduction

There is often debate as to the meaning of the term *chromosphere*. We are all familiar with the Sun's *classical* chromospheric structure (i.e. the VAL model: Vernazza, Avrett & Loeser 1981) — a temperature reversal and rise to ~10,000 K just above the solar photosphere. Observationally, chromospheres present themselves by emission features of singly ionized metals caused (presumably) by an enhanced-temperature region in the outer atmosphere of the star. Theoretically, the chromosphere has been described by Linsky (1980) as an enhanced-temperature region above the stellar photosphere, mechanically heated to temperatures in the range from $T_{\rm eff}$ to ~10,000 K. However, what is the structure of this enhanced-temperature region for a given star? Is it similar to the semiempirical *solar-like* VAL

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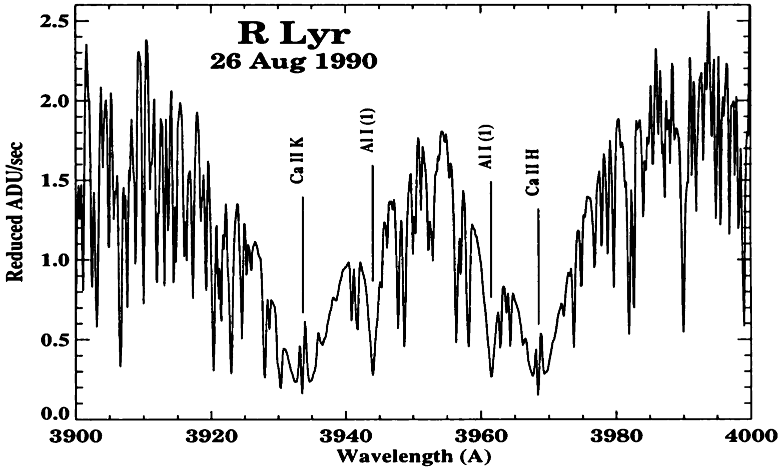

Figure 1. McMath–Pierce spectrum of R Lyr (M5 III) in the Ca II H & K region. Note the strong emission peaks near the cores of these lines which indicates the existence of a chromosphere in this star.

model? Or is it similar to theoretical, *dynamic* shock models that have been calculated for pulsationally unstable stars (e.g. Bowen 1988)?

The first evidence that chromospheres may exist in carbon stars was reported by Bidelman & Pyper (1963), when they identified emission features in the 3250–3300 Å region of TX Psc as Fe II (1), (6), and (7) from ground-based observations. However, comparisons of synthetic spectra to the IUE spectra of TX Psc suggest that these emission features may be *peaks* in the flux between the many strong absorption lines in this region of the spectrum (Luttermoser 1988). Surprisingly, no chromospheric features have been noted in the *non-Mira* N–type carbon stars at visual wavelengths ($\lambda > 4000$ Å). Also, the optically bright, semiregular (SR) N–type stars lack Hα in either emission or *strong* absorption (Yamashita 1972, 1975), as is demonstrated quite nicely in Figure 6 of Johnson et al. (1995). Also, unlike their oxygen-rich counterparts (e.g. R Lyr in Figure 1), the Ca II H & K lines display no chromospheric emission cores as demonstrated in the spectrum of TX Psc in Figure 2. With the advent of ultraviolet (UV) astronomy in the early 1980s, the question of chromospheres in carbon stars could be addressed again. Querci et al. (1982) detected no IUE flux for two SR N–type carbon stars (Y CVn and WZ Cas) and two Mira-type cool carbon stars (U Cyg and SS Vir). From this they deduced that either cool carbon stars have no permanent chromospheres, or substantial overlying opacity from carbon condensates *hides* this chromospheric emission.

However, Johnson & O'Brien (1983) were successful in detecting the UV spectra of 3 other N–type carbon stars (BL Ori, TX Psc, and T Ind). Later,

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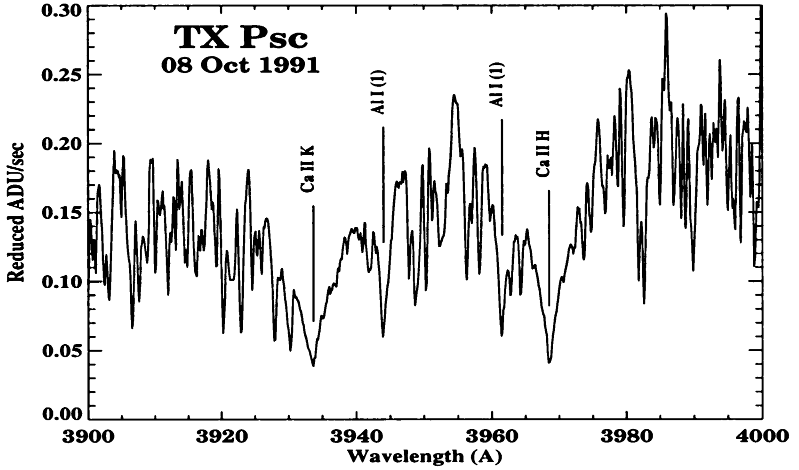

Figure 2. McMath–Pierce spectrum of TX Psc (N0) in the Ca II H & K region. Note the lack of emission in the cores of these lines.

Eaton et al. (1985) reported on the UV spectra of R–type carbon stars, with the late R stars (R5–R8) having UV chromospheric emission similar to late K and M stars. The strongest features seen in the N–type stars are the Mg II h & k lines near 2800 Å and the C II] (UV 0.01) intersystem multiplet near 2325 Å, as can be clearly seen in Figure 4 of Johnson & Luttermoser (1987). The strength of the Mg II lines in carbon stars is similar to that of the coolest non-Mira M–type giant stars.

Querci & Querci (1985) first reported on carbon-star UV emission line variability in the IUE spectra of TW Hor. At least a factor of 3 variation in the Mg II flux was observed, and this was used to empirically deduce a short-period acoustic wave model for the atmospheric structure of this star. They summarize from this work that the chromosphere of TW Hor is extended with a gradual temperature rise. Shortly thereafter, Johnson et al. (1986) found a factor of 8 variability in the Mg II line strength for TX Psc and a factor of 5 for the C II] (UV 0.01) multiplet. This sets the SR variable carbon stars apart from their oxygen-rich counterparts which typically display no more than a 10% variation in emission-line strength (Judge et al. 1993). Indeed, this amount of variability is consistent with that observed for oxygen-rich Mira variables (e.g. Brugel, Willson & Cadmus 1986).

2. Semiempirical Model Chromospheres

To determine the temperature structure of the UV emission-line regions, past studies often employed the technique of semiempirical chromospheric modeling (Linsky 1980). In this technique, one attaches a temperature rise (as a function of column mass or height) to a radiative equilibrium photospheric model representative of the star in question. Adjustments then are made to this temperature rise until the calculated synthetic spectrum matches the observed spectrum. Figure 2 of Luttermoser, Johnson & Eaton (1994) demonstrates this technique, which was used to semiempirically deduce the chromospheric structure of the M6 giant star g Her.

Early attempts at chromospheric modeling of carbon stars, based on low-dispersion IUE spectra of TX Psc, were made by Avrett & Johnson (1984) and de la Reza (1986). Avrett & Johnson found that the Mg II k line can be produced to within a factor of 2 – 5 of its observed strength while producing no Hα emission. However, no C II] (UV 0.01) emission was produced from this model.

TX Psc is perhaps the most important carbon star in the sky since it is one of the brightest and also lies in the ecliptic. Because of this, an angular diameter is known from lunar occultation, which, in turn, allows us to make an absolute flux comparison between synthetic and observed spectra. Prior to HST, only one high-dispersion IUE spectrum existed for an N–type carbon star, that of TX Psc (Eriksson et al. 1986). As such, TX Psc was chosen to be the prototypical N–type carbon star for the chromospheric structure study of Luttermoser et al. (1989). This model was to become known as the LJAL model.

From this work, Luttermoser (1988) and Luttermoser et al. (1989) noted that NLTE must be used to model the outer atmospheres of these stars, and the effects of partial redistribution is important in the formation of the Lyα and the Mg II resonance lines. Also, getting background opacities correct is of the utmost importance when trying to model the chromospheric features, particularly for Mg II, where the Ca I bound-free opacity from the metastable $4p\ ^3P^o$ state (edge at 2940 Å) and the Mg I (UV1) line wing dominate *all* background opacities. The LJAL model was able to reproduce (excluding the circumstellar absorption) the Mg II h & k profiles (Figure 3), match the integrated flux of the C II] (UV 0.01) multiplet, and yet produce no Balmer line emission. To achieve this fit, the chromosphere must have low enough densities and the temperature gradient great enough to prevent the strong neutral metal lines from going into emission, yet produce the proper Mg II and C II] flux (Luttermoser et al. 1989).

The Mg II and C II] emission arises in a region of the atmosphere that is close to the photosphere ($\sim$ 2–3 % of $R_\star$). Therefore, the plane-parallel assumption in hydrostatic equilibrium (HSE) was sufficient to reproduce the Mg II profiles. Much was learned concerning the NLTE radiative transport in cool, low-density atmospheres. The radiative *detailed balance* approximation is *not* valid for the Lyα line despite its enormous optical depth

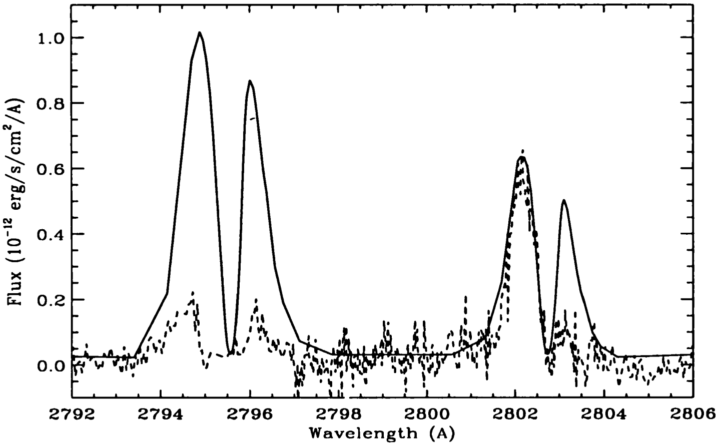

Figure 3. NLTE synthetic profiles from the LJAL chromospheric model of TX Psc (*solid line*) as compared to the high-resolution IUE spectrum (*dashed line*) of this star. Note that circumstellar absorption from Mn I (UV1) and Fe I (UV3) *hides* much of the emission of the k line.

(Luttermoser & Johnson 1992). This is due to the fact that cool temperatures produce collisional rates smaller than the net radiative rates for strong resonance lines. This had a large impact on the excited and ion states of hydrogen and on the strength of the Hα line (see Figure 12 in Luttermoser & Johnson 1992). Also, the ionization and excitation of neutral metals in the upper photosphere are strongly influenced by UV chromospheric photons flowing back down. Photospheric lines must be carefully selected when carrying out abundance analyses for these stars. Strong lines should be avoided since they will form in the upper photosphere or chromosphere.

3. Future Modeling with HST Data

Johnson and collaborators (Johnson et al. 1995; Carpenter et al. 1997) have obtained several FOS (see Figure 1 of Johnson et al. 1995) and GHRS (Figure 4) spectra of N–type carbon stars. The *red light leak* compromises the usefulness of the HST/FOS spectra for these stars. However, the GHRS spectra, with its superior resolution, signal-to-noise, and dynamic range as compared to IUE, have presented additional chromospheric indicators to refine the NLTE semiempirical models. One of the new discoveries was a new emission line, Fe I (UV45) [$z\,^5$H° (J=5) $\rightarrow$ $a\,^5$F (J=4)] at 2807 Å, which was never previously seen in a cool giant star spectrum. Actually, this feature appeared in the original IUE spectrum but was partially hidden by a cosmic ray hit. As part of the Johnson et al. team, D. G. Luttermoser identified this feature as Fe I (UV45) and suggested that it is a fluoresced

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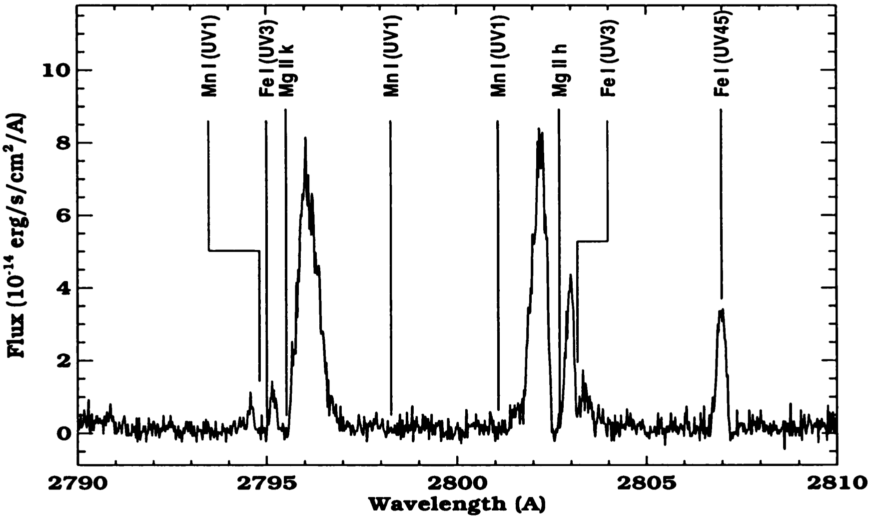

Figure 4. HST/GHRS spectrum of TX Psc. Note that the effects of the circumstellar absorption overlying the k line now can be clearly seen in this spectrum. The fluorescent Fe I line at 2807 Å is discussed in the text.

line since other lines in this multiplet were not seen in emission. However, no suitable pump was found in Moore's UV Multiplet tables. Another member of the team, R. F. Wing, then carried out calculations that showed that an Fe I transition in the UV13 multiplet should have a line at 2325.32 Å [$a\,^5$D (J=4) $\rightarrow z\,^5$H° (J=5)] which does not appear in the multiplet tables. This lies virtually on top of the strongest line in the C II] (UV 0.01) multiplet. Later, when the TX Psc spectrum in the C II] region was obtained, the effect of this pump was seen in the C II] line at 2325.40 Å (Figure 5).

Also note the substantial changes seen in the Mg II profiles between the IUE spectrum (31 May 1984) and the GHRS spectrum (4 Dec 1994). Does this result from changes in overlying absorption or from changes in the actual Mg II strength? Although changes in the opacity of the overlying circumstellar shell certainly plays a part in the variability of the Mg II lines, comparing the GHRS spectrum to the IUE spectrum certainly makes a strong case for actual changes in the chromospheric emission region of the atmosphere. The differences in these spectra provide probable evidence for a non-static chromosphere for carbon stars.

Is the LJAL model a reasonable one to describe the chromosphere of TX Psc and carbon stars in general? Luttermoser, Johnson & Eaton (1994) showed that the Mg II and C II] features of g Her could not be simultaneously modeled with an HSE, 1–D, plane-parallel atmosphere. The final g Her chromosphere model was based on fitting the Mg II profiles. However, this model produced C II] line ratios that were inconsistent with the IUE

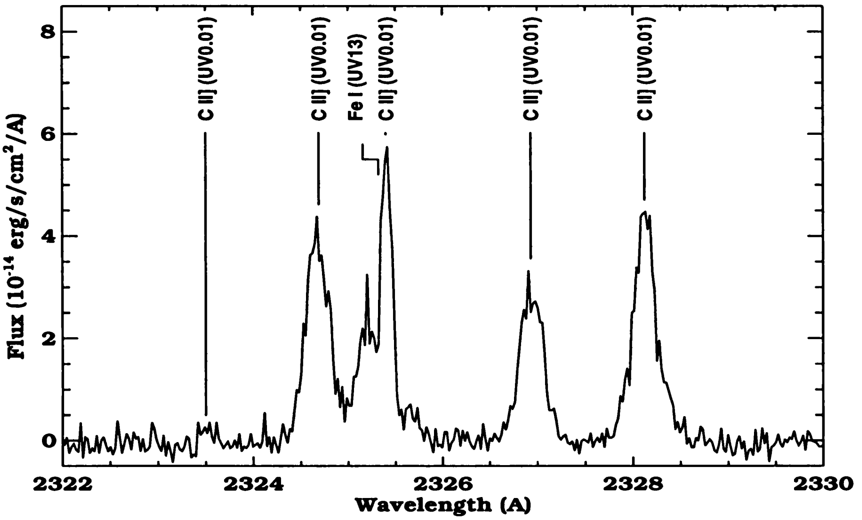

Figure 5. C II] (UV 0.01) profiles in the GHRS spectrum of TX Psc. Note the overlying absorption from Fe I (UV13) near the C II] λ2325.40 line that gives rises to the fluoresced emission feature at 2807 Å.

observations. The C II] lines indicated that the electron density in the line-emitting region had to be increased by two orders of magnitude to achieve the proper fit. Since these C II] lines form at the same depths in the model as the Mg II peak flux (i.e. the inner chromosphere), this would require either moving the chromosphere inward or enhancing the temperature of the inner chromosphere. Neither of these techniques would work, since moving the chromosphere inward would produce strong emission in the Mg I (UV1) and optical 'b' lines, and in Hα. Meanwhile, enhancing the temperature in the inner chromosphere would produce much too broad Mg II emission. Hence the assumptions used in the model cannot be valid. With the HST data, we can now compare the synthetic C II] profiles from the LJAL model to the observed lines. As was the case with g Her, the C II] line ratios from the model for TX Psc are inconsistent with the observations. The C II] lines indicate that the electron density must be higher by a factor of 100 with respect to the final HSE model. Essentially, we need to force C II] to form in a different atmospheric region than the Mg II lines. Luttermoser et al. (1998) show that this can be done with *dynamic* models.

Finally, Jørgensen & Johnson (1991) have also shown that the LJAL model should produce emission cores in the infrared CO and HCN lines — but none are observed! Are the chromospheres of carbon stars inhomogeneous? Jørgensen & Johnson suggest that they are, having a chromospheric filling factor less than 10%.

4. Conclusion

The era of semiempirically modeling the chromospheric structure of carbon stars and late-type M giant stars is over — the *classical* semiempirical method (i.e. a 1–D, HSE, homogeneous atmosphere) produces inconsistent results! So what must be done to achieve more realistic models for the outer atmospheres of these stars? First, NLTE techniques must be incorporated. Second, dynamical processes must be included, both long-period and short-period waves. Finally, inhomogeneities may also have to be included should the CO and HCN emission problems still exist in the radiative-hydrodynamic calculations. Can we answer the question: *What mechanism(s) heats the chromospheres of these stars?* The answer is NO, not yet! But with the HST data as a guide and more sophisticated modeling efforts, we can start to approach the correct answer.

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References

Avrett, E. H. & Johnson, H. R. 1984, in *Cool Stars, Stellar Systems, and the Sun*, ed. S. L. Baliunas & L. Hartmann (Springer-Verlag), p. 330

Bidelman, W. P. & Pyper, D. M. 1963, *PASP*, 75, 389

Bowen, G. H. 1988, *ApJ*, 329, 299

Brugel, E. W., Willson, L. A. & Cadmus, R. 1986, in *New Insights in Astrophysics: 8 Years of UV Astronomy with IUE*, ed. E. J. Rolfe, ESA, SP–263, p. 213

Carpenter, K. G., Robinson, R. D., Johnson, H. R., Eriksson, K., Gustafsson, B., Pijpers, F. P., Querci, F. & Querci, M. 1997, *ApJ*, 486, 457

de la Reza, R. 1986, in *The M–Type Stars*, ed. H. R. Johnson & F. R. Querci, NASA, SP–492, p. 373

Eaton, J. A., Johnson, H. R., O'Brien, G. T. & Baumert, J. H. 1985, *ApJ*, 290, 276

Eriksson, K., Gustafsson, B., Johnson, H. R., Querci, F., Querci, M., Baumert, J. H., Carlsson, M. & Olofsson, H. 1986, *A&A*, 161, 305

Johnson, H. R., Baumert, J. H., Querci, F. & Querci, M. 1986, *ApJ*, 311, 960

Johnson, H. R., Ensman, L. M., Alexander, D. R., Avrett, E. H., Brown, A., Carpenter, K. G., Eriksson, K., Gustafsson, B., Jørgensen, U. G., Judge, P. D., Linsky, J. L., Luttermoser, D. G., Querci, F., Querci, M., Robinson, R. D. & Wing, R. F. 1995, *ApJ*, 443, 281

Johnson, H. R. & Luttermoser, D. G. 1987, *ApJ*, 314, 329

Johnson, H. R. & O'Brien, G. T. 1983, *ApJ*, 265, 952

Jørgensen, U. G. & Johnson, H. R. 1991, *A&A*, 244, 462

Judge, P. G., Luttermoser, D. G., Neff, D. H., Cuntz, M. & Stencel, R. E. 1993, *AJ*, 105, 1973

Linsky, J. L. 1980, *Ann. Rev. Astron. Astrophys.*, 18, 439
Luttermoser, D. G. 1988, Ph.D. Thesis, Indiana University
Luttermoser, D. G., Bowen, G. H., Willson, L. A. & Brugel, E. W. 1998, in preparation
Luttermoser, D. G. & Johnson, H. R. 1992, *ApJ*, 388, 579
Luttermoser, D. G., Johnson, H. R., Avrett, E. H. & Loeser, R. 1989, *ApJ*, 345, 543
Luttermoser, D. G., Johnson, H. R. & Eaton, J. A. 1994, *ApJ*, 422, 351
Querci, F., Querci, M., Wing, R. F., Cassatella, A. & Heck, A. 1982, *A&A*, 111, 120
Querci, M. & Querci, F. 1985, *A&A*, 147, 121
Vernazza, J. E., Avrett, E. H. & Loeser, R. 1981, *ApJ Suppl.*, 45, 635
Yamashita, Y. 1972, *Ann. Tokyo Astr. Obs.*, 13, 169
Yamashita, Y. 1975, *Ann. Tokyo Astr. Obs.*, 15, 47

Discussion

Dorfi: In the case of chromospheres, it must be important to include a pulsational model to have an appropriate inner boundary condition for your calculations.

Luttermoser: Yes, very much so since such boundary conditions will be important for the strength (i.e. temperature) of the outward-propagating shocks, which of course has a major impact on the emergent spectrum and *global* structure of the atmospheric model.

Little–Marenin: Are your models affected by the fact that TX Psc has no dust emission? Is the spectrum of UU Aur, which does have dust emission, significantly different from that of TX Psc?

Luttermoser: It won't affect the NLTE model of TX Psc at all, since we neglected dust in those calculations. Does dust affect the UV spectra of UU Aur (and other "dustier" carbon stars)? The UV spectra of many of the optically bright carbon stars (both GHRS and IUE low-dispersion) look very similar (see Johnson & Luttermoser 1987). However, some of the optically bright N stars have no observed UV flux (Y CVn is a good example). The presence of dust probably has a major impact on the UV spectra of these stars.

Totten: I find it surprising that you say no N–type C stars have been found with emission lines, because Sanduleak & Pesch reported an N–type star with Hα and Hβ emission in 1984 or 1986. Also, the APM high galactic latitude survey has observed several N–type stars which have distinctive Hα and Hβ emission lines. All of these are "classical" cool N–type stars with no known variability.

Luttermoser: Thank you for that information. Actually, I had tremendous difficulty keeping Hα in absorption in my modeling attempts. Perhaps I should have qualified that comment by saying, "no *optically bright*, non-Mira N–type carbon stars have been observed with Hα emission." The

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fact that some semi-regular variable (by the way, "classical" N–type carbon stars, i.e. the SR and Lb variables, vary in brightness by at least a few tenths of a magnitude) N–type carbon stars are observed as hydrogen Balmer emission carbon stars (like Miras) further supports my claim that the atmospheric structure of these stars is similar to the Mira variables.

Whitelock: In support of what you say about SRs and Miras, the IR and optical observations suggest that the difference between SRs and Miras is quite ambiguous in the case of C-rich stars.

Luttermoser: I agree 100 %! The UV spectra of these stars also point in that direction.

Elitzur: SiO maser observations indicate the presence of magnetic fields of order 2–10 gauss. Leaving out the effect of magnetic fields may involve the neglect of a leading dynamic factor.

Luttermoser: This may be the case. I ignored magnetic fields mainly due to the fact that it is already difficult to carry out NLTE radiative transfer calculations in these low-density atmospheres, especially when one relaxes the plane-parallel assumption and includes macroscopic velocity fields. It has been argued in the past that due to their large sizes and slow rotation rates, these cool giants should have negligible magnetic fields since the dynamo effect should be very weak. However, recent observations of "hot spots" on the surfaces of these stars (e.g. HST observations of α Ori by A. Dupree) suggest that this might not be a correct assumption. Perhaps rising granules give rise to a surface magnetic field. I, myself, won't touch such radiative-magneto-hydrodynamic calculations with a "ten-foot pole."

Wing: Some people have expressed skepticism that the Fe I fluorescence mechanism you mentioned can be effective if the pump line at 2325 Å is only a predicted transition that is not listed in the Multiplet Tables. I would like to add that this is a rather special transition, namely the one that raises neutral iron from its ground state (in fact, from the lowest sublevel of the ground state) to the upper state of the observed emission line at 2807 Å. And if you ask why this pump line is not included in the Multiplet Tables when the other lines of the same multiplet are listed, I propose that this is due to the same coincidence with C II λ2325 that causes the fluorescence in carbon stars — there may have been some soot on the electrodes used in producing the laboratory Fe I spectrum!

Luttermoser: Thank you for that explanation. I have no doubt that this Fe I (UV 13) transition exists. The fact that you predicted it from the appearance of the fluoresced 2807 Å line before the TX Psc C II (UV 0.01) spectrum was obtained is more than enough proof for me.

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