OBSERVATIONS OF MASS LOSS AND CIRCUMSTELLAR MATTER AROUND COOL CARBON STARS

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Abstract. Spectroscopy and infrared photometry of carbon stars show three distinct forms of circumstellar matter. IRAS 12311–3509 probably has an edge-on disk and the spectrum is dominated by resonance emission from atoms and molecules in the vicinity. The long-period variables V Hya and R Lep are undergoing deep fadings, apparently caused by dust formation around the star, while variable emission from circumstellar gas is seen. The semiregular variable T Mus showed absorption bands from very cool material during an unusual episode in 1994.

1. Introduction

Hoyle and Wickramasinghe (1962) predicted the formation of dust particles in the atmospheres of carbon stars. Excess infrared emission from some variable stars, including V Hya and R Lep which are discussed below, first revealed the presence of circumstellar dust (Woolf & Ney 1969; Gillett, Merrill & Stein 1971). More recent work on V Hya includes the discovery of an extended envelope with bipolar structure (Tsuji et al. 1988; Kahane, Maizels & Jura 1988). Another object discussed here, IRAS 12311–3509, probably has unresolved bipolar structure.

The fading and reddening of carbon Miras in the visible and the near infrared was found by Bessell & Wood (1983), Feast et al. (1984), and Le Bertre (1992). Percy et al. (1990) noted that such fading episodes were common in the visual light curves of carbon-rich Mira variables. Mattei & Foster (2000) report trends for some of these stars observed over 90 years, while Whitelock (2000) gives near-infrared light curves for several carbon variables and notes the occurrence of RCB-like dips in the light curve of R For.

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2. IRAS 12311–3509

IRAS 12311–3509 has a large excess at *L* and a unique optical spectrum characterised by emission of SiC_2 bands and of resonance lines of the alkali metals (Lloyd Evans 1991b). This was interpreted as an example of a star which is hidden by a dusty disk but seen by reflection from material out of the plane of the disk, as in the case of Herbig's (1970) model for the somewhat similar M star VY CMa. The emission lines and bands are produced by resonance emission from circumstellar gas, as in the case of cometary spectra. The star appears unresolved on the UK Schmidt Sky Survey photographs, whereas VY CMa appears in double-star catalogues as a complex object, but since IRAS 12311–3509 is 7 mag fainter, it is probably more distant and appears unresolved as a result.

Sarre, Hurst & Lloyd Evans (1996, 2000) have analysed the SiC_2 bands in the light of recent laboratory and theoretical work on the molecule. The particular suite of bands which appears strongly in emission is consistent with radiative excitation of cool material, while the band profiles indicate a temperature of a few hundred K.

Spectra taken over the period 1989–1996 show no significant change, nor do infrared observations taken near the extremes of this interval show a significant difference. This is consistent with the presence of a disk. The other stars discussed here show much more dynamic behaviour.

3. T Mus

T Mus is a semiregular variable with periods of 93 and 1082 days (Lysaght 1989). It is a J star with strong SiC_2 bands (Keenan 1993). T Mus was observed frequently from 1986 onwards to study spectral changes round the complex light cycle. The spectrum changes considerably, presumably as the result of temperature changes at the photospheric level; the spectrophotometric gradient in the 4700–5200 Å region and the C_2 bandhead at 4737 Å are especially variable. The SiC_2 bands also vary in intensity, though as with other carbon variables observed in the present programme the different bands seen in this spectral region maintain similar relative strengths. The spectrum showed a much greater change in appearance during the 1994 observing season when T Mus should have been on the declining part of the slow light variation (Lysaght 1989). The different SiC_2 bands no longer varied in step: several became very weak while the rest showed a narrower profile than usual.

The recent laboratory results for SiC_2 provide an explanation for this behaviour also (Sarre, Hurst & Lloyd Evans 1996, 2000). The missing bands are all "hot" bands, whereas those which remain strong are formed by absorption from the lowest vibrational level. The narrow profile indicates a rotational temperature below that typical of the stellar photosphere. Both observations show that the bands are formed in gas substantially cooler than that found even in the photospheres of Mira variables at any stage of their light cycle. This gas may be circumstellar; alternatively it may represent a substantial temporary extension of the normal photosphere.

4. Dust Minima in the Mira Variables

The early infrared and visual observations which led to the discovery of the dust fading events in carbon-rich long period variables were not supported by spectroscopic observations. We have spectroscopic observations covering a ten-year period for two Miras, R Lep and R For, the SRa star R Scl, and V Hya which is also an SRa of relatively small amplitude but in addition fades by 3 mag or so every 18 or 19 years. *JHKL* photometry has been obtained during faint episodes of these stars. V Hya entered a deep minimum in 1992 and appears to be in the recovery stage now, while R Lep has been fading on average for some years and entered a deeper phase with spectacular spectroscopic consequences in 1994. R For has shown more modest phenomena of this type, while R Scl has been relatively inactive though it is believed to have suffered major mass loss in the past.

4.1. DUST FADINGS AND INFRARED COLOURS

The long runs of visual observations of Mira variables by the AAVSO (Mattei, Mayall & Waagen 1990) allow the detection of those stars with prominent dust fading events. The stars which undergo fadings with an amplitude greater than one magnitude are redder in the *J-K, K-L* diagram than those with more constant mean light (Lloyd Evans 1997). The three stars noted above are redder during the fading in each case. Lloyd Evans (1997) used both *JHKL* and IRAS data to show that the infrared colours from $1.2\,\mu$m to $12\,\mu$m are correlated with the amplitudes of the fadings in visual magnitude. Since these colours are often taken as a measure of the rate of mass loss, it seems that for carbon Miras, at least, the fading episodes represent individual epochs of mass loss. The visual fading as well as much of the reddening in the near infrared must result from absorption by newly formed circumstellar dust.

4.2. C_2 EMISSION DURING DUST FADING EPISODES

The most radical spectroscopic change seen in conjunction with the fading of visual light is the appearance of C_2 emission. This is seen first at the (0,0) bandhead at 5165 Å. This bandhead is normally a strong absorption feature without any emission, whereas the (1,0) 4737 Å bandhead is

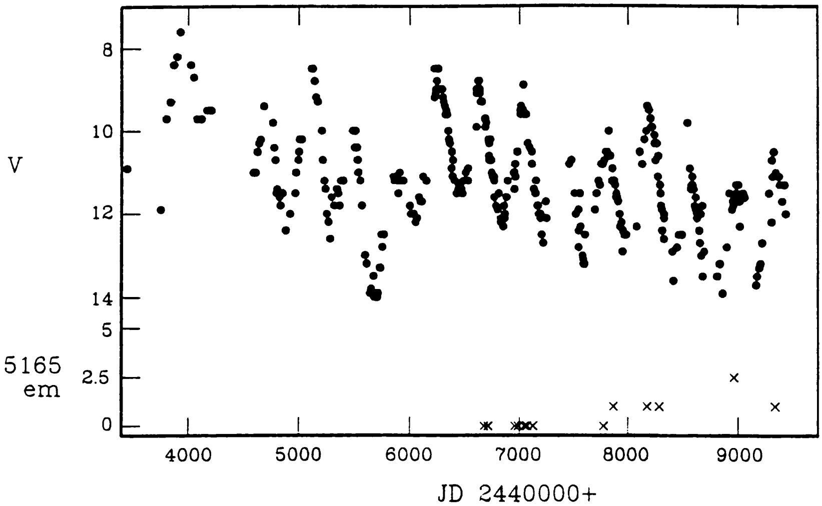

Figure 1. The visual light curve of R For from Southern African amateur observations (*above*), and the estimated emission intensities at the 5165 Å (0,0) bandhead of C_2 (*below*).

regularly seen in emission during part of the pulsation cycle (Lloyd Evans 1989). The emission at 5165 Å may be very intense so that the usual strong absorption band is reversed, when enhanced emission is also seen at 4737 Å (Lloyd Evans 1997). A truly quantitative estimate of the emission strength is hard to make because of the loss of the fiducial point provided by the now-obscured base of the absorption band, and qualitative estimates were made on a scale from 0 = absent to 5 = strong. Figure 1 shows a plot of emission against time for R For, with the visual light curve above it. The spectroscopic data are sparse because R For is too faint to be observed near minimum light. C_2 emission was absent when the star was bright early on, but as the mean light faded emission of moderate strength appeared. Lloyd Evans (1997) found that V Hya had no emission at 5165 Å despite almost invariably strong emission at the (1,0) bandhead until the deep minimum of 1992–95 when intense emission appeared. R Lep showed increasingly strong emission as the star faded slowly, especially from 1994 onwards. The mean light of R Lep varies almost continuously, with deep minima at intervals of about 40 years (Mayall 1963), and by 1995 the pulsation minima were as faint as had been observed at any time in the past.

4.3. ATOMIC LINE EMISSIONS

The ten-year observing programme also covered the Na D lines and Hα. V Hya showed no emission at Na D before the deep minimum. The farther red region of the resonance lines of K I and Rb I was only observed routinely after the fading was well established, although an early observation showed no emission a year before the start of the deep minimum. The absence of emission at K I before the fading began was established by Barnbaum, Morris & Kahane (1995) who reported only absorption at low velocity from May 1988 to January 1993. We found weakened absorption of Na D in July 1992 and emission in December 1992, weak emission of K I in July 1993 and strong emission in December 1993 and emission of Rb I from December 1993. Hα emission maintained the same cyclic behaviour that it exhibited before the fading started. The latter may indicate that the pulsation and the near-photospheric levels of the atmosphere were unaffected, which would be expected if the activity is a phenomenon of the circumstellar region as some theories predict (Fleischer, Gauger & Sedlmayr 1992; Winters et al. 1994). The Na and K lines showed a P Cygni structure. The blueshift of the absorption component corresponded to a velocity of 100 km s^{-1} relative to the photosphere. This is in the range found previously for the bipolar outflow from V Hya (Tsuji et al. 1988; Kahane, Maizels & Jura 1988; Sahai & Wannier 1988; Lloyd Evans 1991a). The circumstellar gas may be accelerated outwards in the bipolar flow so that this velocity is not typical of mass-losing carbon stars in general.

R Lep differs in that the fadings are less discrete and more of an ongoing continuous variation in mean light, as can be seen by comparing its light curve (Mayall 1963) with that of V Hya (Mayall 1965). The Na D absorption varies greatly round the 427 d light cycle and becomes weak near maximum light. It was so weak near maximum light in 1994 that K I and Rb I were observed for the first time and found to be in emission. These lines varied little in the following two years, whereas Na D continued its normal variation between strong absorption and near disappearance; the weakness in 1994 was not highly abnormal when seen in perspective (see Figure 2). P Cygni structure has not been seen with certainty.

4.4. THE COMPANION OF V HYA

V Hya is atypical in having a companion. This was suspected from the unusual velocity-broadening of the photospheric absorption lines, attributed to rotation resulting from the star having been spun up by a companion (Kahane, Maizels & Jura 1988; Barnbaum, Morris & Kahane 1995). These authors favour a common envelope system, as opposed to the accretion disk about a detached companion postulated by Sahai & Wannier (1988) to drive the rapid bipolar flow. Continued observation of the violet spectral region in the six years since the observations of a blue continuum by Lloyd Evans (1991a) has shown that the continuum has both high and low inten-

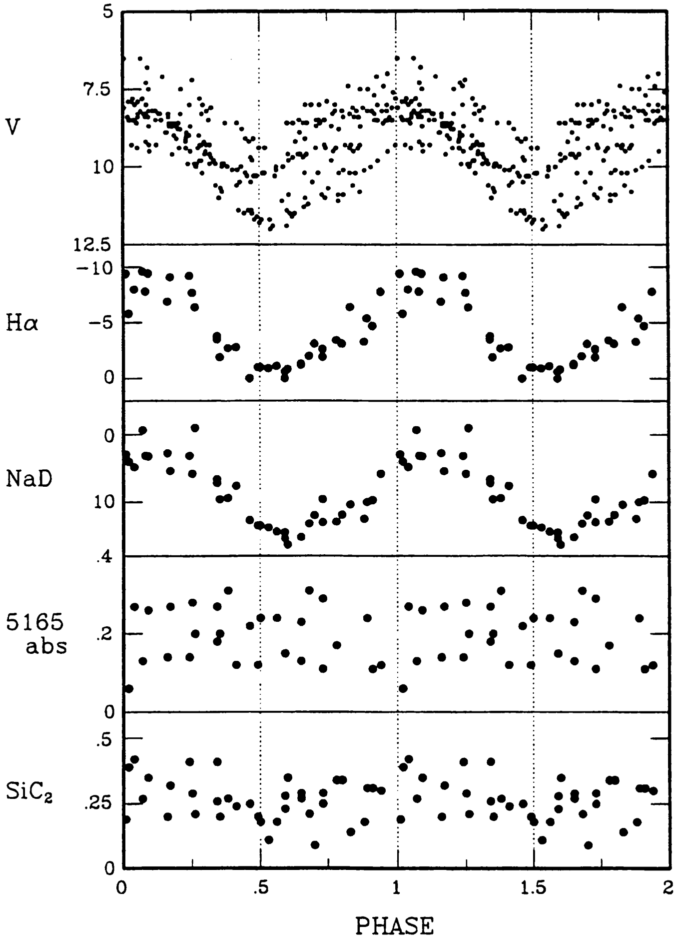

Figure 2. Phase dependence of magnitude and spectroscopic parameters for R Lep. The visual magnitude and the C_2 and SiC_2 absorptions do not repeat well as the star enters a dust fading, but Hα emission and Na D absorption show little scatter. Note that there is weak net emission of Na D after light maximum on occasion.

sity states, each with its characteristic line spectrum. The spectrum is that of an accretion disk and does not match that of any normal star. Barnbaum, Morris & Kahane (1995) doubted the presence of an accretion disk because of the weakness of the UV continuum observed by IUE, a point also made by Luttermoser in discussion at this meeting. V Hya is surrounded by dust at all times and that may suffice to obscure the accretion disk in the UV. The Mg II emission seen in IUE spectra is likely to arise in the jet rather than to be of chromospheric origin. The continuum intensity at

4160 Å, which has been calibrated spectrophotometrically, also faded and brightened roughly in phase with the deep minimum of the carbon star although the amplitude was less. This is attributable to the same additional circumstellar absorption that affected the visual light of the carbon star. This observation excludes the possibility that the slow fading of the carbon star results from the extinction when it is on the near side of its orbit and is obscured by a dusty circumbinary disk. The accretion disk would be expected to be least obscured then, when it is on the far side of its orbit, unless it is indeed a close companion in which case a second more distant companion would have to be postulated to account for the size of the orbit.

4.5. AN ADDITIONAL PERIODICITY IN V HYA

The several atomic and molecular features which have been measured in R Scl, R For, R Lep and V Hya (avoiding the disturbed intervals for the last two stars) show time-dependent variations. The pulsation period of the carbon star is the principal determinant of the variations. V Hya completed nearly four cycles in its 530 d pulsation between the start of observation and the onset of the deep minimum. Most spectroscopic features followed this period, but the strength of the (0,0) band of C_2 at 5165 Å did not and may instead follow a period of double this length. This band is very strong in V Hya and it is probably formed at a high level in the atmosphere.

4.6. A HIGH-TEMPERATURE PHASE IN V HYA

The visual observations of V Hya showed the first departures below the normal light curve in the early months of 1992, and the spectrum had a unique appearance when observed in February and April. This was the only time when the pulsation-related emission of C_2 at 4737 Å disappeared and a strong absorption band appeared. The (0,0) band of C_2 at 5165 Å remained strong while the continuum in this spectral region was much flatter than on any other occasion. The whole appearance was that of a considerably hotter carbon star. It seems likely that the steep spectral continuum of a cool carbon star is related to the presence of a very distended atmosphere, and a possible explanation of this unusual observation is that the outer atmosphere of V Hya lifted off, becoming optically thin, to reveal a layer below, which would be hotter until it had time to adjust to the normal state of the star. The situation appeared normal in July 1992, by which time Na D absorption began to weaken.

The deep minima of R Lep and V Hya are still continuing. Long-term spectroscopic and photometric monitoring of these stars will be required to give a complete picture of these events. There is a need for spectroscopic observations of higher resolution and also for other types of observation such as spectropolarimetry.

I am indebted to the members of the Variable Star Section of the Astronomical Society of Southern Africa for data on these stars, and to Audrey van der Wielen for the diagrams.

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Discussion

Luttermoser: I have obtained (as yet unpublished) low-resolution LWR IUE spectra of V Hya for an approximately 5–month duration in 1994. There was no evidence of an accretion disk (i.e. a hot continuum) in these spectra. Indeed, all of these spectra display "normal" N–type stellar chromospheric emission — Mg II and C II (2325 Å) emission lines. Can you comment as to why we don't see V Hya's accretion disk at UV wavelengths?

Lloyd Evans: The dust obscuration was strong then and may have hidden the accretion disk, which normally has the color temperature of an F star (7000 K). It is also possible, given the lack of velocity data, that these lines are formed in the 160 $\mathrm{km\,s^{-1}}$ shock region which shows Ca II emission as well as [Fe II], [S II], etc.

Giridhar: For V Hya the periodicity from C_2 lines is twice that from optical features. A similar observation is found for the RV Tau star R Sct where infrared features give a period of 140 days whereas optical features give 70 days. The explanation offered was that optical spectral features formed near the photosphere experienced two shocks whereas infrared features formed in the outer layers experienced only one. Alternatively, non-sphericity such as a prolate or oblate shape could cause two different periods.

Lloyd Evans: It is interesting that in this respect, as well as that of the double periodicity, V Hya may have something in common with the RV Tauri stars.

Kerschbaum: When looking at your sketch of the geometry of IRAS 12311–3509, I wonder if it would not be helpful to have some polarimetric measurements to find out what comes from the star and what from its vicinity?

Lloyd Evans: Spectropolarimetry would be very valuable. We do not have the equipment to do this.

Gustafsson: Since R Scl shows extended resonance scattering (in Na D and K I λ 7699) at least out to $\sim 10'$ from the star (see the poster by Gustafsson et al., these Proceedings), it might be rewarding to monitor it with a set of different slit lengths.

Lloyd Evans: I agree. Our spectrograph has only two channels (star, sky) so I have not attempted this.