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Period and chemical evolution of SC stars

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ABSTRACT

The SC and CS stars are thermal-pulsing asymptotic giant branch stars with a C/O ratio close to unity. Within this small group, the Mira variable BH Cru recently evolved from spectral type SC (showing ZrO bands) to CS (showing weak C_2). Wavelet analysis shows that the spectral evolution was accompanied by a dramatic period increase, from 420 to 540 d, indicating an expanding radius. The pulsation amplitude also increased. Old photographic plates are used to establish that the period before 1940 was around 490 d. Chemical models indicate that the spectral changes were caused by a decrease in stellar temperature, related to the increasing radius. There is no evidence for a change in C/O ratio. The evolution in BH Cru is unlikely to be related to an ongoing thermal pulse. Periods of the other SC and CS stars, including nine new periods, are determined. A second SC star, LX Cyg, also shows evidence for a large increase in period, and one further star shows a period inconsistent with a previous determination. Mira periods may be intrinsically unstable for C/O $\approx$ 1; possibly because of a feedback between the molecular opacities, pulsation amplitude, and period. LRS spectra of 6 SC stars suggest a feature at $\lambda > 15$ μm, which resembles one recently attributed to the iron-sulphide troilite. Chemical models predict a large abundance of FeS in SC stars, in agreement with the proposed association.

Key words: stars: AGB and post-AGB – stars: fundamental parameters – stars: individual: BH Cru.

1 INTRODUCTION

The observed properties of stars on the asymptotic giant branch (AGB) are largely determined by the ratio of carbon to oxygen in their atmospheres. Carbon abundances in AGB stars increase due to dredge-up following their regular thermal pulses. After a series of these events, which happen every 10^4–10^5 yr, the enhanced carbon may cause a transition from an oxygen-rich star to a carbon-rich star, via the intermediate S-stars (e.g. Lloyd Evans 1984).

The SC stars (Keenan & Boeshaar 1980) form a continuous spectral sequence intermediate between the S and C stars (Catchpole & Feast 1971). They show very strong sodium D-lines, and strong CN bands (Stephenson 1973), and either weak ZrO bands (SC stars) or C_2 bands (CS stars). The molecular abundances indicate a C/O number ratio very close to unity, so that CO formation leaves little C or O for the other molecules.

The SC star BH Crucis has simultaneously been found to show a unique combination of a lengthening period (Bateson, McIntosh & Venimore 1988; Walker & Marino 1991; Walker, Ives & Williams 1995), and evolution in spectral type from SC to CS (Lloyd Evans 1985), with ZrO bands (Catchpole & Feast 1971) disappearing and the C_2 band appearing. The spectral evolution has been interpreted as being due to an increase in C/O ratio (Whitelock 1999). Both the period and abundance changes have been suggested to be caused by a recent thermal pulse (Wood & Zarro 1981, Whitelock 1999). BH Cru could therefore present a unique case of real-time AGB evolution.

In this paper we present an analysis of the light curve of BH Cru, to quantify the period and amplitude variation. Chemical modelling is used to investigate whether the change in relative molecular

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Table 1. Visual and infrared magnitudes of BH Cru, as given in Walker (1979) and Whitelock et al. (2000).

Filter	U	B	V	R	I	J	H
	K	L	A_V	F_{12}	F_{25}	F_{60}	
BH Cru	13.03	10.12	7.41	5.94	3.32	3.24	2.07
	1.58	1.25	0.5	20.9 Jy	6.6 Jy	1.6 Jy	

abundances can be explained as being due to a decrease in effective temperature, at constant C/O ratio. We also present new periods for other SC stars, including two stars that may show period changes similar to BH Cru.

2 PULSATION IN BH CRU

2.1 The star

BH Cru (also known as He 120) was reported to be variable by Welch (1969), and assigned a spectral type of SC 4.5–7 (Keenan 1971; Keenan & Boeshaar 1980). The star is bright, reaching a visual magnitude of 7, with an amplitude between 1^m and 3^m. Whitelock, Marang & Feast (2000) suggest a distance of d = 900 pc, from the Mira *PL* relation. At Galactic metallicity, carbon stars form for initial masses $\gtrsim 2\ M_{\odot}$ (Groenewegen & de Jong 1993, their table 5). The galactic z-height of BH Cru of approximately 100 pc is consistent with such a progenitor star. A strong Sr I 4607-Å line shows evidence for s-process element enhancements.

Optical photometry from Walker (1979) and infrared photometry from Whitelock et al. (2000) are listed in Table 1. The colours are typical for unobscured carbon stars, and the *IRAS* flux densities are consistent with photospheric emission. The $K - [12] = 0.96$ colour gives a blackbody temperature of 3000 K, identical to the stellar temperature (Section 3.3 below). There is no evidence for on-going mass loss, neither from self-obscuration in the near-infrared, nor from a mid-infrared dust excess. The lack of mass loss is unusual for such a long-period Mira.

2.2 Recent period evolution

We have analysed visual observations collected by the Royal Astronomical Society of New Zealand (RASNZ). Only data from individual observers contributing 15–20 observations or more for each star were used. The light curve was binned into 20-d averages and analysed using wavelet transforms, which have the advantage of being sensitive to changes of the pulsation properties (period, amplitude) over time (e.g. Bedding et al. 1998). We have used the weighted wavelet Z-transform (WWZ, Foster 1996) developed at the AAVSO specifically for unevenly sampled data.

The visual light curve is shown in the top panel of Fig. 1. During the 1970s, the maxima tended to be flat and long-lived, with pronounced but shorter-lasting minima. From 1990 onward, the maxima became more pronounced and slightly brighter, with a hump on the ascending part that is very common among Mira variables. In the first few years, the light curve also showed a secondary minimum superposed on the plateau of maximum. Double maxima and minima of alternating depth are not uncommon among the longer-period Miras, e.g. R Cen (Hawkins, Mattei & Foster 2001). In R Dor (Bedding et al. 1998), a split maximum preceded a change in pulsation mode.

The wavelet plot of BH Cru confirms the period evolution first reported by Bateson et al. (1988). The second panel of Fig. 1 shows the pulsation frequency as a function of time, where the contours represent the significance level. The 'best' period is plotted in the bottom panel. From 1970 until around 1995, we see a steady increase in the period, since 1995, the period has been more or less constant. The period was 425 d at the time of discovery (1969), 500 d in 1990 and 535 d in 1999. This large increase of over 25 per cent within (at most) 20 yr is unparalleled: among known Miras, only T UMi (Gál & Szatmáry 1995; Mattei & Foster 1995) has shown a comparable, but opposite, change. The new case of LX Cyg (Templeton, Mattei & Price 2003) is discussed further below.

Although the period evolution shows some possible fluctuations, it can be fitted well with a constant rate of change of 5 d yr^{-1}, corresponding to 1.4 per cent per cycle, between 1975 and 1995. (The pre-1970 part of the curve shows a reverse change, but this may be affected by edge effects in the wavelet analysis.)

The semi-amplitude (third panel of Fig. 1) shows similar strong evolution. It was around 0.8 mag before 1980 and, in parallel with the period increase, the semi-amplitude rapidly increased to 1.4 mag in approximately 1992. Except for a single faint maximum in AD 2000, the amplitude has since remained constant.

Fig. 2 illustrates the correlation between the increases in amplitude and period. It shows a roughly linear correlation, with the semi-amplitude increasing by approximately 50 mmag $cycle^{-1}$, or approximately 5 per cent per cycle. The correlation between period and semi-amplitude evolution mirrors that seen in R Hya (Zijlstra, Bedding & Mattei 2002), and also in R Aql and S Ori (Bedding, Conn & Zijlstra 2000) and Y Per (Kiss et al. 2000).

2.3 Older period data

Although BH Cru was only discovered to be variable in 1969, the region has been extensively covered by older surveys. However, we have not found published records of BH Cru prior to 1969. The star is absent from the CP catalogue (Gill & Kapteyn 1900), but this has a completeness limit of 9.2 mag and the blue magnitude of BH Cru is always below this. The deeper CD catalogue (Thome 1932) goes to 10 mag, but also does not include it. These limits do not allow for an unambiguous interpretation. We have therefore searched the Harvard plates for evidence of its pre-discovery behaviour.

The Harvard Plate Stack contain 96 good observations of BH Cru, 15 detections with uncertain magnitude, and 37 plates where the star is not visible. The plates are almost exclusively blue. Combined with the $B - V$ of BH Cru, the star exists near the limit of the plates while at maximum. The data are shown in Fig. 3. We performed a wavelet analysis using the 96 good and 15 uncertain determinations, and also included upper limits where they were fainter than 11.8 mag (the brighter limits do not constrain the variability).

BH Cru was a pulsating variable well before its discovery as such. Strong pulsations are evident, with an amplitude between 1 and 2 mag. The plates before 1910 are consistent with little or no fluctuations, but the sampling is poor and this is not conclusive. The data are too patchy for a well-determined period, however, a period of approximately 490 d is indicated around 1940. The period at 1930 may have been slightly shorter (approximately 440 d).

Compared with Fig. 1, the period around 1940 was approximately 10 per cent longer than in the early 1970s. The data suggest that the period was not constant even in this early phase and there may have been a further increase shortly after 1940. Further data would be desirable, but the conclusion from the available data is that between 1945 and 1970 the period must have decreased. The recent period instability may be part of a recurrent behaviour.

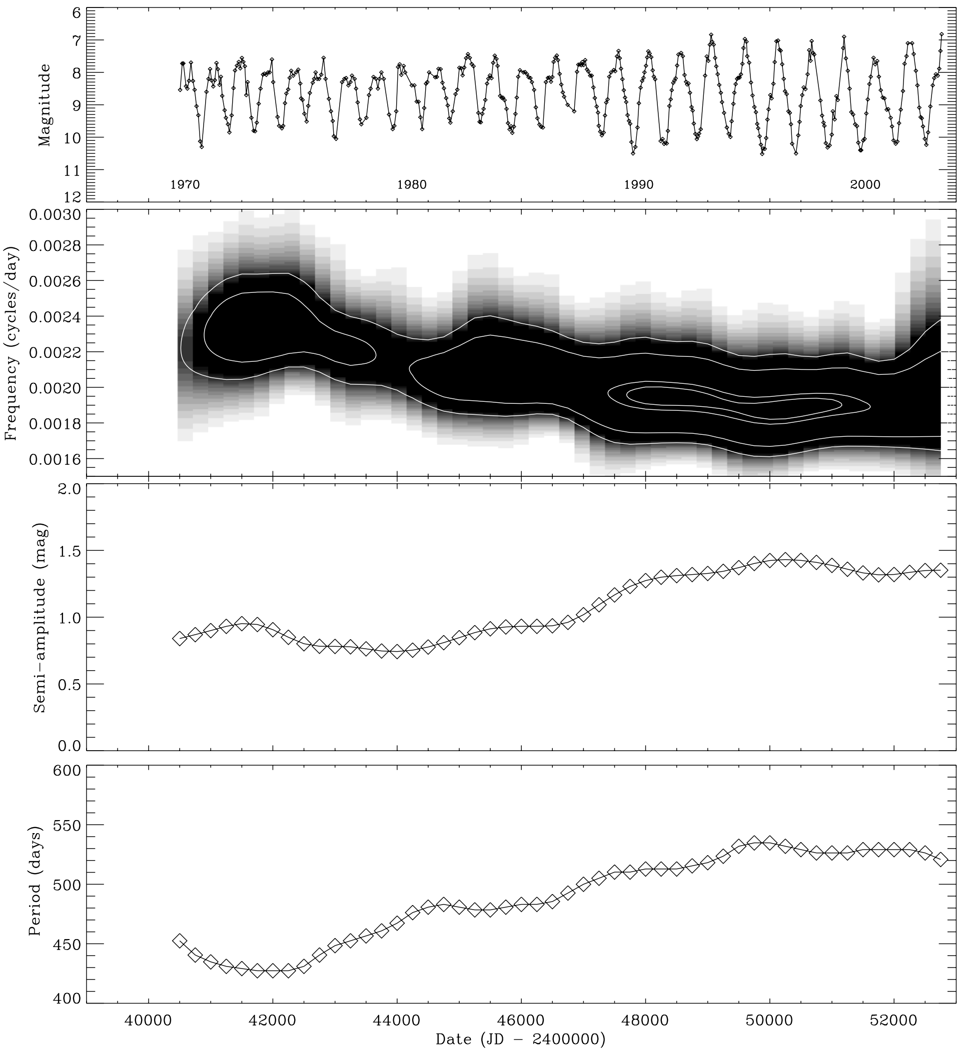

Figure 1. The wavelet analysis for BH Cru 1970–2002, based on visual observations. The light curve, the frequency, the semi-amplitude of the main frequency component and its period are shown.

2.4 Physical changes in BH Cru

The pulsation equation for Mira variables is

$$\log P = 1.5 \log R - 0.5 \log M + \log Q \quad (1)$$

for first overtone pulsators, where the pulsation constant $Q \approx 0.04$ (Fox & Wood 1982), or

$$\log P = 1.949 \log R - 0.9 \log M - 2.07 \quad (2)$$

for fundamental mode pulsators (Wood 1990). P is the period in days and R and M are the radius and mass in solar units.

In Mira variables, M decreases on times of scales of 10^5–10^7 yr because of the stellar wind, but over a century it is approximately constant. In any case, BH Cru shows no evidence for large mass loss. Q can be assumed as constant on this short time-scale. The radius R is not directly known; it is, however, the only parameter where the changes can explain the period evolution of BH Cru.

Miras are thought to be fundamental-mode pulsators, although this is not as well determined for the very long period variables. However, the observed optical radii for Miras are much larger than those predicted from the fundamental mode, and agree better with first overtone pulsators (Haniff, Scholz & Tuthill 1995). The discrepancy may be due to missing opacity in the atmosphere models. van Belle, Thompson & Creech-Eakman (2002) find increased diameters also at K, which they attribute to circumstellar (water) emission. Here we prefer equation (1) since it better fits the atmospheres.

The period of BH Cru increased by 25 per cent since 1970, corresponding to a 16 per cent change in the radius from equation (1). For a stable bolometric magnitude, this would decrease the effective temperature by 7.5 per cent: ∼250 K at the temperature of 3200 K (Loidl, Lançon & Jørgensen 2001). Fundamental-mode models require a smaller radius change (12 per cent) and temperature change (∼200 K).

If the luminosity also increased, a smaller temperature decrease would be required. The mean magnitude of the infrared light curve changed by no more than 0.1 mag, between 1980 and 1995, and the $J - K$ colour reddened by no more than 0.05 mag. The bolometric correction at K therefore decreased by less than 0.05 mag, using fig. 16 of Whitelock et al. (2000). The mean magnitude of the optical light curve was constant to within 0.5 mag but it is much more sensitive to temperature variations and varying molecular opacity. Overall, the data are consistent with evolution at constant luminosity; any increase in the luminosity did not exceed 10 per cent.

Assuming an initial radius of 300 $R_\odot$, BH Cru will have expanded by 6×10^{10} m, at an average velocity of ~ 100 m s^{-1}.

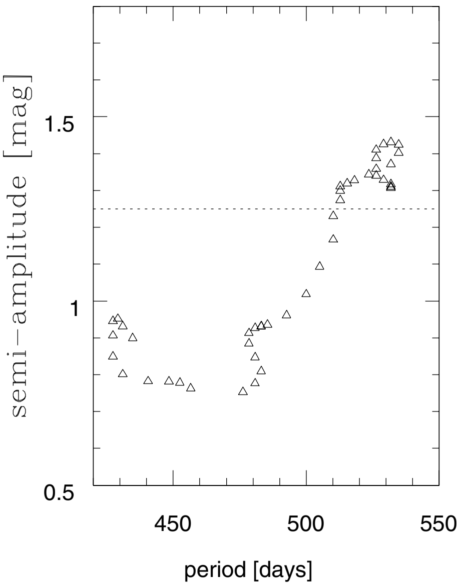

Figure 2. The visual semi-amplitude, in magnitudes, versus the period in days, since JD 244 1000 (AD 1970). The dotted line shows the lower limit of the Mira classification.

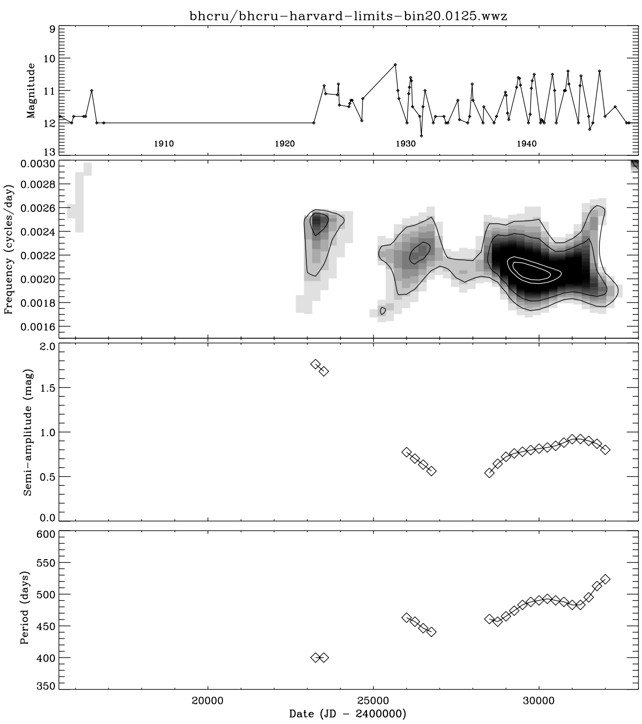

Figure 3. Photographic observations of BH Cru in 20-d bins. Upper limits, where a comparison star of the that magnitude could be seen, are included if at $m = 11.8$, but brighter limits are not. The systematic photometric accuracy of the data is no better than 0.5 mag. Period and amplitude before JD 242 5000 have very low confidence.

Typical small-amplitude Mira variables expand at 3–10 km s^{-1} during the pulsation cycle. The small average expansion velocity would therefore not be expected to significantly disrupt the pulsational behaviour.

3 EQUILIBRIUM CHEMISTRY: ZrO AND C_2

3.1 Spectral changes

The spectral evolution of BH Cru is remarkable. Before 1973, BH Cru showed evidence for ZrO, but lacked C_2 lines (Catchpole & Feast 1971); the ZrO line was weak or absent around 1970 (Keenan 1971) but strong in 1967 (Stephenson 1973); Catchpole & Feast (1971) reported it as weakly present on an undated plate. In 1980, lines of C_2 had appeared and the ZrO lines were no longer present (Lloyd Evans 1985). The spectra taken around 1980 cover a substantial part of the light curve: cyclical variability cannot account for the observed evolution (Lloyd Evans 1985). The few spectra taken around 1970 show ZrO lines of variable strength: during some part of the pulsation cycle, the pre-1973 spectra may have been lacking in ZrO as well. However, the strong ZrO bands visible at times before 1973 did not re-occur over any part of the pulsation cycle in 1980.

The change has been interpreted as tracing an increase in the C/O ratio from <1 to >1 (Whitelock 1999), associated with the dredge-up of carbon produced in a helium shell flash (a thermal pulse). However, below we investigate whether the change in effective temperature of the star can also explain the abundance changes, without requiring a change in the C/O ratio. We note that a possible recurrent shift in spectrum between the presence of ZrO and C_2 has been seen in TT Cen (Stephenson 1973).

A temperature effect is indicated by the fact that SC stars tend to have earlier subtypes than CS stars. Only two SC stars (see Appendix A) are known to reach types later than SC5 (BH Cru and LX Cyg), while three of the five CS stars are classed as C7 or later. The temperature zero point for C and S stars subclasses differ: C5 corresponds in temperature to approximately M0. However, SC7 and C7 have similar temperatures (Keenan & Boeshaar 1980), and the late CS stars have therefore lower stellar temperatures than any of the SC stars with known subclass.

3.2 Temperature dependence

To investigate the temperature and C/O dependence in isolation of other parameters, we model the photospheric composition as a molecular equilibrium (e.g. Tsuji 1973; Wyckoff & Clegg 1978; Tarafdar 1987; Sharp & Huebner 1990). We calculate the molecular equilibrium composition by a direct minimization of the Gibbs free energy of the system using a steepest descent technique (White, Johnson & Dantzig 1958). The free energy of the system is given by

$$G = \sum_i f_i x_i, \tag{3}$$

where x_i is the number of moles of molecule i and f_i is the chemical potential of molecule i,

$$f_i = \left(\frac{G}{RT}\right)_i + \ln P + \ln\left(\frac{x_i}{\bar{x}}\right). \tag{4}$$

Here, $(G/RT)_i$ is the Gibbs free energy of formation of molecule i, P is the total pressure of the system (a model parameter), and $\bar{x} = \sum_i x_i$. The Gibbs free energy of formation of a molecule is a temperature-dependent thermo-chemical property that can be found for example in the JANAF tables (Chase et al. 1985). To estimate the value at other temperatures, we used an interpolation formula. Sharp & Huebner (1990) provide coefficients to a polynomial fit of the form

$$\Delta G = aT^{-1} + b + cT + \mathrm{d}T^2 + eT^3, \tag{5}$$

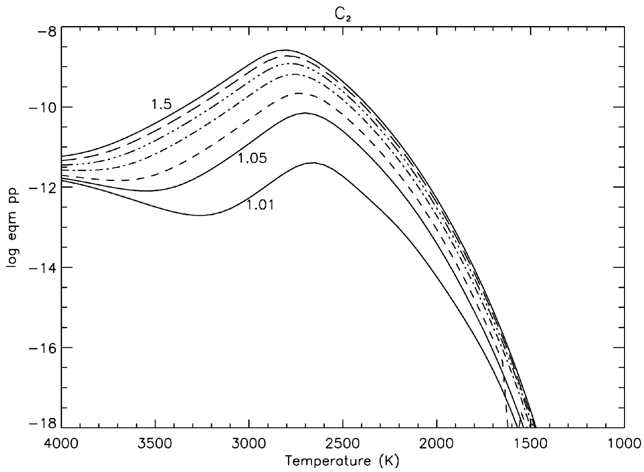

Figure 4. The equilibrium partial pressure of C_2 (log), as a function of temperature, for seven different values of the C/O ratio: 1.01, 1.05, 1.1, 1.2, 1.3, 1.4 and 1.5 (lower curve to upper curve, respectively).

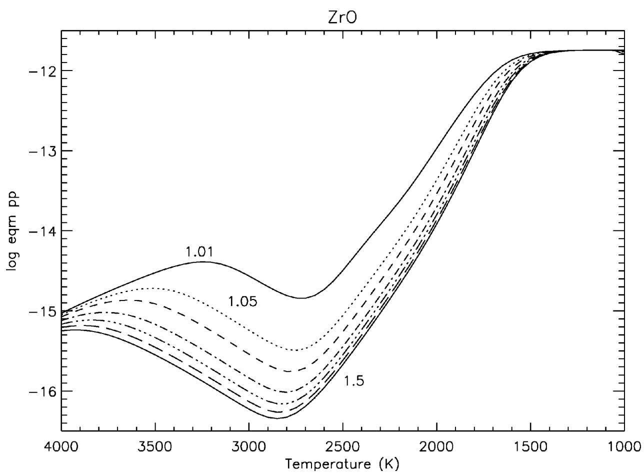

Figure 5. Same as in Fig. 4, but for ZrO.

to the Gibbs free energies for 210 species using JANAF data. We added further species appropriate to AGB stars in the same way.

At chemical equilibrium, G is a minimum Zemansky (1957). The equilibrium composition is therefore the set of mole numbers $X = \{x_i\}_{i=1,n}$ which minimizes G. Full details of the minimization technique subject to these constraints can be found in Markwick (2000).

We adopt solar elemental abundances (Cameron 1973; Anders & Grevesse 1989) except for carbon which is enhanced to vary the C/O ratio. Models were run for values of the C/O ratio, between 1.01 and 1.5. The resulting equilibrium abundances of the molecules C_2, ZrO and YO for a variety of temperatures and C/O ratios are shown in Figs 4–6. A plot of the H_2 partial pressure is given in Fig. 7 to allow conversion of the partial pressures into fractional abundances.

Fig. 4 shows clearly that the photospheric abundance of C_2 increases with decreasing temperature over the range 4000–2800 K. Furthermore, the model shows that oxides such as ZrO can still exist at C/O ratio >1, although at reduced abundance (Fig. 5). The relative abundances shown in the figure do not take the s-process enhancements into account. In BH Cru, [Zr/H] $= 1.2$ (Abia & Wallerstein 1998): assuming a linear scaling, the ZrO and C_2 relative abundances are almost equal for C/O $= 1.01$ at $T = 3300$ K. Abia & Wallerstein (1998) give C/O $= 1.02$.

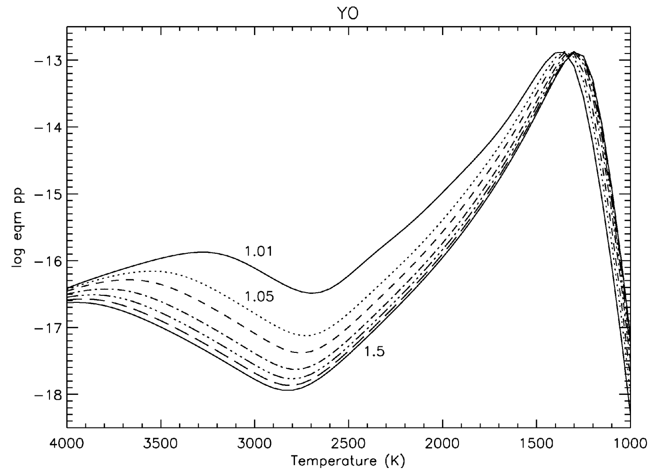

Figure 6. Same as in Fig. 4, but for YO.

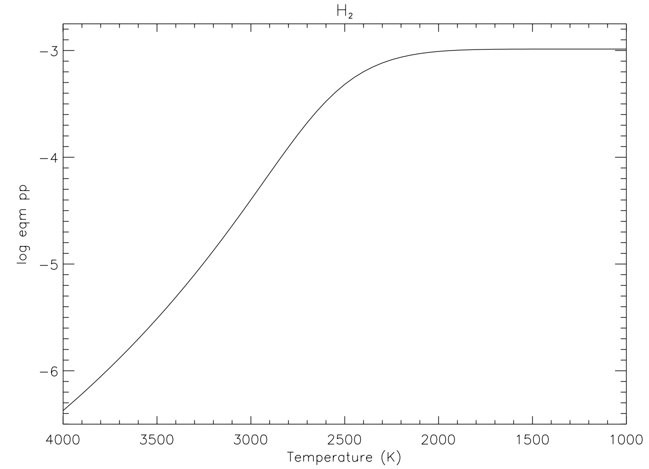

Figure 7. Same as in Fig. 4, but for H_2. Molecular hydrogen is so dominant in the model that the variation with C/O ratio is negligible.

The photospheric temperature of BH Cru is taken as 3200 K (Loidl et al. 2001; these authors found a temperature close to minimum of approximately 2800 K). At these temperatures, Fig. 4 shows that even a relatively small decrease in temperature leads to a large increase in the abundance of C_2: a decrease of 300 K can yield a ten-fold increase. The peak abundance is reached at $T \approx 2800$ K.

The disappearance of ZrO and appearance of C_2 took place between 1973 and 1980 Lloyd Evans (1985). Assuming a constant rate of period evolution, the period increased by ~50 d or roughly 12 per cent over this time. This corresponds to a radius increase of 8 per cent and a temperature decrease of 4 per cent if the luminosity remained constant (assuming first overtone pulsation). The $\Delta T = 130$ K for a current temperature of 3200 K would have increased the C_2 abundance by a factor of 3–5 and decreased the ZrO abundance by a similar factor. The YO abundance should have decreased as well (see Fig. 6), but this molecule has only been weakly detected (Keenan & Boeshaar 1980) and there is no observational mention of a change with time.

3.3 Atmosphere models

The model above has two shortcomings; we do not consider the extended atmosphere, and no time-dependent chemistry is included. Chemical equilibrium is unlikely to hold at the conditions and

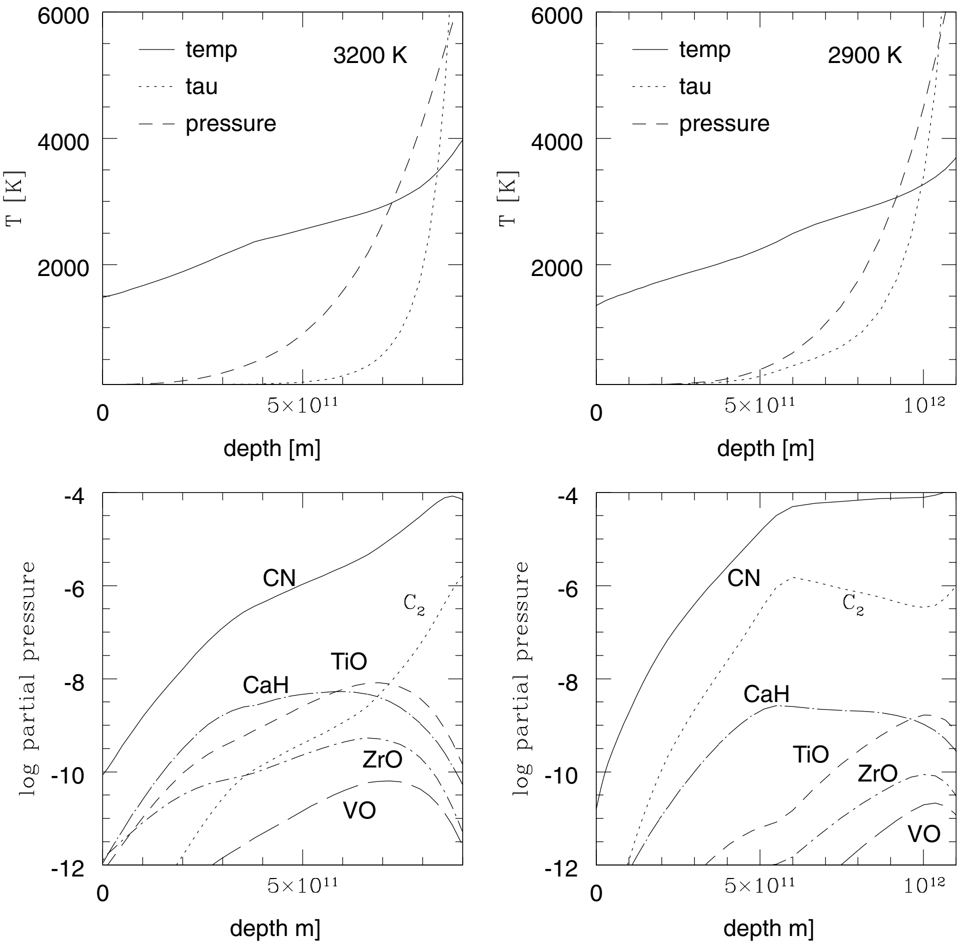

Figure 8. Results of the atmosphere models. Top-left: temperature, density and opacity for a stellar temperature of 3200 K. The stellar surface is on the right. The opacity scale runs from 0 to 1. Top-right: same, for a stellar temperature of 2900 K. Bottom: molecular partial pressures for the two temperatures.

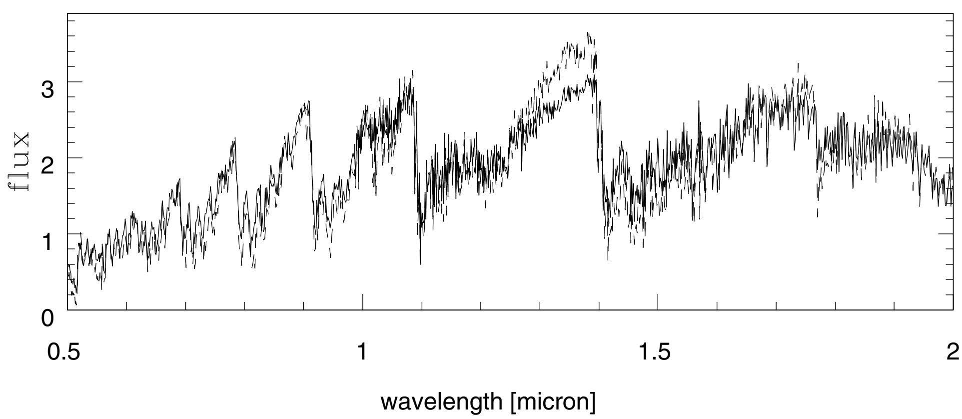

Figure 9. The model spectrum of BH Cru for two temperatures: 3200 K (drawn) and 2900 K (dashed).

dynamic time-scales within an extended pulsation-driven atmosphere. However, we do not attempt to address time-dependent chemistry here.

The extended atmosphere is described using the hydrostatic atmosphere models of Loidl et al. (2001). These models include equilibrium chemistry for a large number of molecules (but excluding e.g. Mg and Fe molecules and CaCl). Opacities are included for seven carbon-star molecules only: CO, CN, CH, C_2, HCN, C_2H_2 and C_3. $C/O = 1.01$ is used. The models are shown in Fig. 8 for two different temperatures, corresponding to two different phases of the pulsation cycle. Comparison between the two temperatures confirms the strong dependence of the oxides and C_2 on temperature. At the higher temperatures, C_2 is mainly present near the photosphere. At the lower temperature, the abundance in the extended atmosphere is much higher. Model spectra at the two temperatures are shown in Fig. 9.

3.4 Optical spectra

The spectra of oxygen-rich Miras variables show few atomic lines due to the absorbing molecular blanket which hides the photosphere. In SC stars, this blanket is transparent and the spectrum is covered in lines (Tsuji 1964).

Infrared spectra of BH Cru are presented by Loidl et al. (2001): they show strong CN and weak C_2 bands. We obtained optical spectra of BH Cru and some comparison SC/CS stars using the double-beam spectrograph at the MSSSO 2.3-m telescope, centred at the 6500-Å ZrO band. The data were taken on 2003 May 18 and 21, under non-photometric conditions. The dispersion is 0.55 Å pixel^{-1} and the resolution is approximately 1 Å. The spectra are flat-fielded using an internal lamp and sky-subtracted. We did not correct for the atmospheric and instrumental response.

The spectra are shown in Fig. 10. Typical noise per wavelength pixel is 1 per cent. The many lines repeat between the spectra, and are largely due to s-enhanced metals (e.g. Abia & Wallerstein 1998).

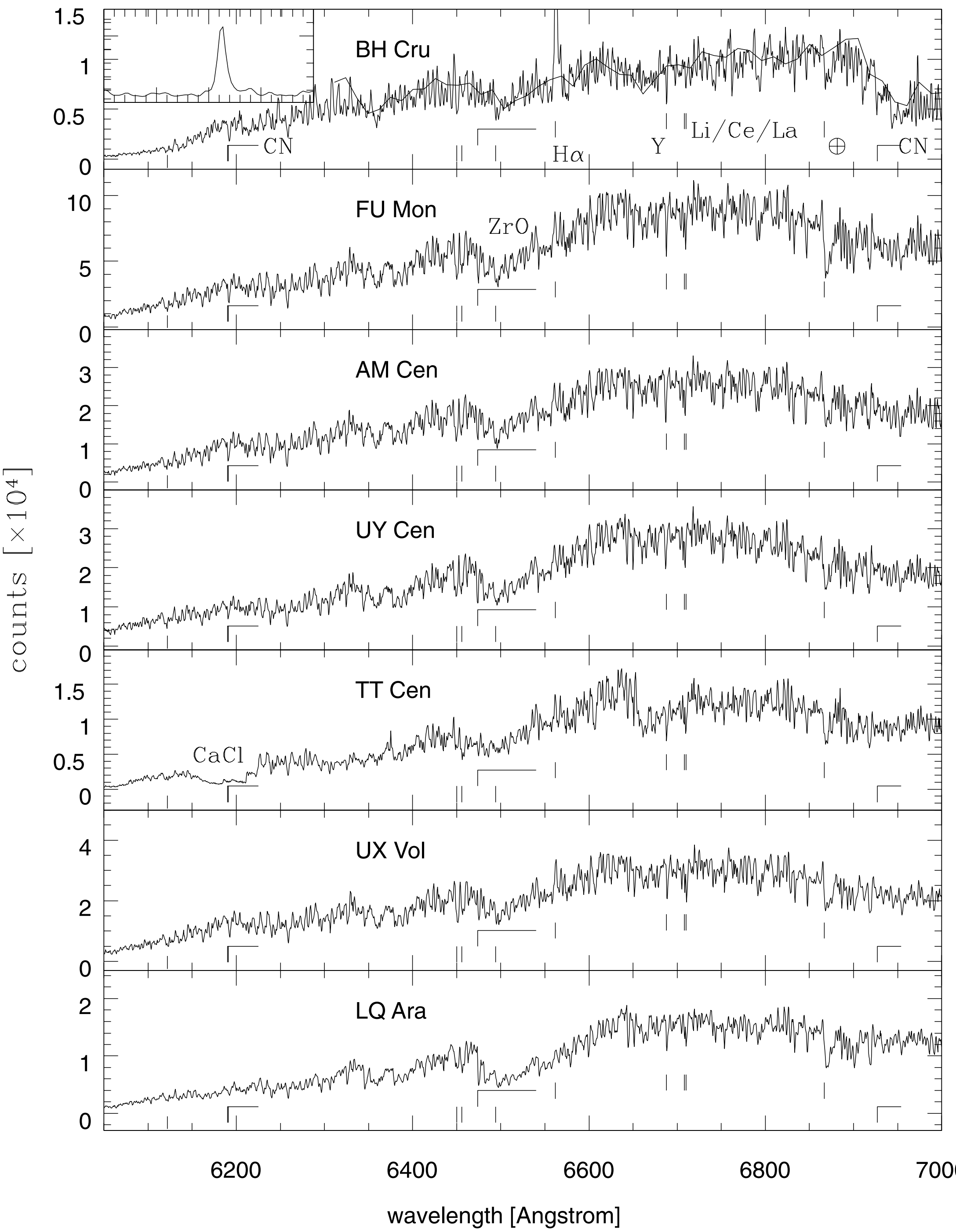

Figure 10. Optical spectra of seven SC/CS stars. The inset shows the (saturated) Hα emission line of BH Cru. The spectra are not response-corrected or flux-calibrated. The strong band at 6857 Å is telluric. The spectrum of BH Cru is shown together with a model for 3200 K. The y-axis gives total counts × 10^{-4} per wavelength pixel; the noise is negligible, and all line features are real. A few lines/bands are labelled; indicated but unlabelled lines/blends are due to CN.

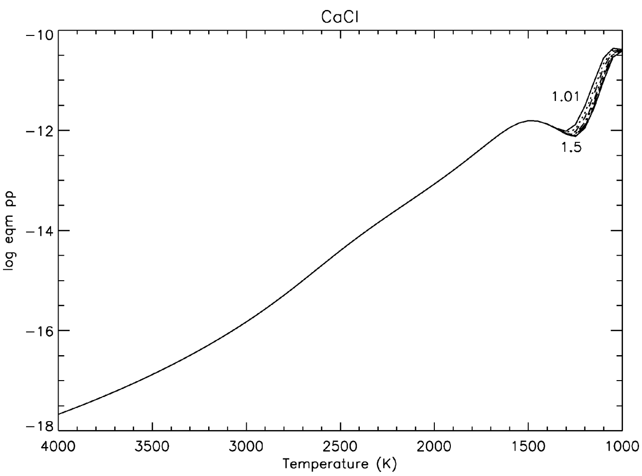

Figure 11. Same as in Fig. 4, but for CaCl.

The 6708-Å line is present in all other spectra but weak or absent in BH Cru. In all cases it is weaker than the adjacent La I 6710 Å. The lithium line overlaps with another line and the identification is not unambiguous (Reyniers et al. 2002).

The model spectrum of BH Cru (see previous section) is shown in the top diagram. The model is for 3200 K: the 2900 K model also gives an acceptable fit. The good fit obtained around 6500 Å confirms the absence of the ZrO band (6474–6540 Å) in BH Cru: the good fit is obtained in spite of this band not being included in the opacities in the model. All other stars which were observed show the band, although with varying strength. The broad 6350-Å ZrO band is similarly seen in all stars except BH Cru.

BH Cru shows possible absorption lines at 6053 and 6070 Å, which differ from the other stars and may be from the C_2 Swan-band. Other lines of the Swan bands at 6190 and 6480 Å are not detected, but the confusion at our resolution is too high to rule out their presence. C_2 is present in BH Cru longward of 7000 Å (Loidl et al. 2001).

The double CaCl band at 6200 Å is seen in TT Cen only. This band is common in carbon stars, but is often blended and masked by strong CN bands. The CaCl abundance depends very little on the C/O ratio (Fig. 11). The CaCl band strength tends to vary over the pulsation cycle (Sanford 1950), being strongest near minimum light: TT Cen was observed near minimum. TT Cen may be compared with VX Aql (Wyckoff & Wehinger 1976), in which CaCl also is the strongest molecular band. Both these stars are long-period Miras. Clegg & Wyckoff (1977) show that CaCl is favoured by high-density environments.

3.5 Dust

Stars with C/O close to unity have difficulty forming dust: the removal of C and O from the chemistry means that neither silicates nor carbon grains can form. It is therefore not surprising that the SC stars show little evidence for significant dust emission. A few *ISO* spectra have very poor signal-to-noise (S/N) ratio at mid-infrared wavelengths, and weak features would not be seen.

We therefore retrieved the *IRAS* LRS spectra of the seven SC/CS stars with 12-μm fluxes above 15 Jy: BH Cru, AM Cen, FU Mon, UY Cen, S Lyr, VX Aql, and WZ Cas. The spectra mostly show adequate but low S/N ratio (the brightest star in the sample, UY Cen, only has $F_{12} = 55$ Jy). In order to emphasize any excess, we have subtracted a pseudo-continuum represented by a λ^{-2} power law that was scaled to the flux at 14 μm for each star.

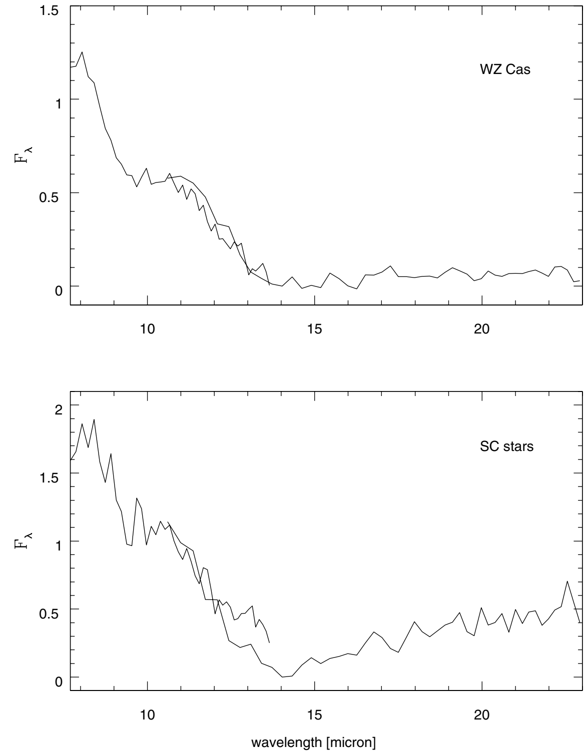

Figure 12. IRAS LRS spectra of SC/CS stars, from which a λ^{-2} pseudo-continuum has been subtracted. Top panel: WZ Cas, the only star showing a silicate-like feature. Bottom panel: average of six other SC stars.

The top panel of Fig. 12 shows the resulting spectrum of WZ Cas. The impression of a weak silicate feature is deceptive: it reflects a deep CS absorption feature at 8 μm.

None of the other SC LRS stars resembles WZ Cas. We have co-added the remaining six spectra and again subtracted a pseudo-continuum to produce a 'typical' SC-star LRS spectrum (lower panel of Fig. 12). Compared with WZ Cas, the continuum-subtracted spectrum rises beyond 15 μm. The wavelength coverage is insufficient to decide whether this is a dust continuum or a broad feature. However, the rise resembles that seen in some young stellar objects, where it is part of a feature peaking at 23 μm. This feature has previously been attributed to FeO, but Keller et al. (2002) found a fit to the iron-sulphide troilite. Hony et al. (2002) report the same feature and presumably the same mineral in planetary nebulae, and suggest a carbon-star origin. If the SC stars show the same feature, it would strongly support the identification with troilite, as formation of this mineral should benefit from the removal of O from the dust formation.

Figs 13 and 14 show the calculated equilibrium abundances of FeO and FeS. As expected, FeO declines sharply as the C/O ratio increases. FeS also shows a decline but is less sensitive especially at photospheric temperatures. At all but the lowest temperatures, FeS is the more abundant molecule by three orders of magnitude. The formation of an iron sulphide such as troilite would therefore not be unexpected. However, the evidence for a troilite feature is weak and this point remains to be confirmed.

Ferrarotti et al. (2000) suggest that FeSi would be the main dust component in S stars. This mineral has bands at 32 and 50 μm. ISO SWS spectra are available for three SC stars: WZ Cas, S Lyr and W Cas. The S/N ratio is low and no emission can be seen longward of 30 μm.

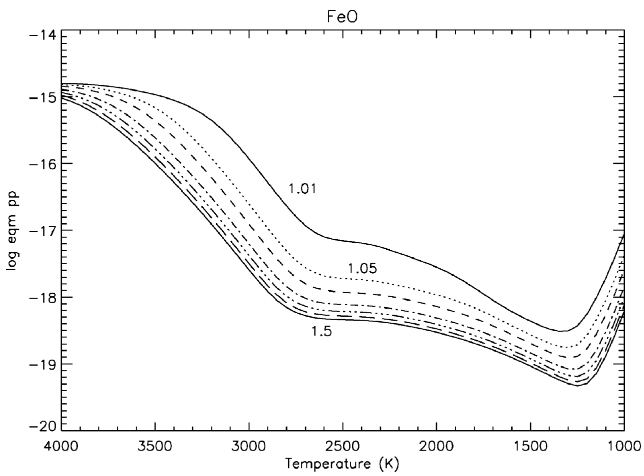

Figure 13. Same as in Fig. 4, but for FeO.

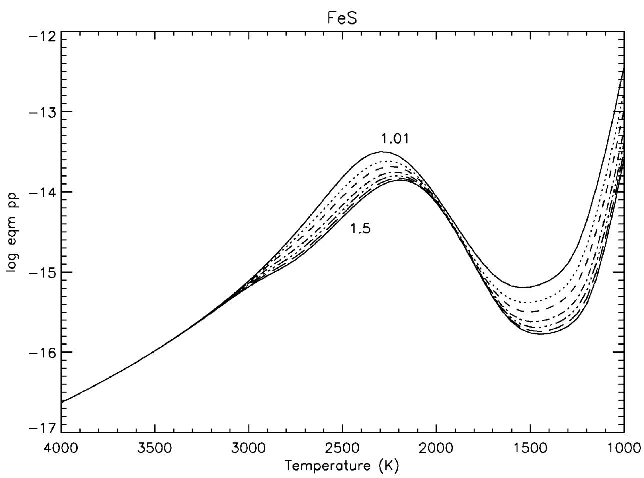

Figure 14. Same as in Fig. 4, but for FeS.

Evidence for mass loss in BH Cru comes from a blueshifted (by 19 km s^{-1}) possible rubidium line Abia & Wallerstein (1998). Otherwise, the SC stars show little evidence for significant mass loss. [Of the stars in Table A1 (see the Appendix), only FU Mon was detected in CO and a mass-loss rate of 10^{-7} $M_{\odot}$ yr^{-1} derived with a very low expansion velocity (2.8 km s^{-1}, Jorissen & Knapp 1998).] This is in marked contrast to the oxygen-rich Miras and carbon Miras, even though the SC stars form an intermediate evolution. It is, however, understandable, as the mass loss is driven by radiation pressure on dust. SC stars are expected to form a phase of mass-loss interruption (Zijlstra et al. 1992) while evolving from an oxygen-rich to a carbon-rich star.

4 LX CYG: ANOTHER BH CRU

Large period changes similar to BH Cru are very rare among Mira variables: Zijlstra & Bedding (2003) describe six cases, including R Hya. They estimate that the type of evolution seen in BH Cru occurs in ∼1 per cent of well observed Miras, over a century of observations. To find one on-going case among the small group of SC/CS stars (16 in total) would be unexpected. To find a second one would suggest a correlation between the rare spectral class and the period evolution.

There is in fact a second case of period evolution among the SC stars. LX Cyg is an SC3 star with a catalogued (GCVS) period of 465 d. An increase of its period was independently discovered by Alksne & Alksnis (1985) and by Broens, Diepvens & Van Der Looy (2000) and Templeton et al. (2003). Templeton et al. (2003) have analysed an extended data set. They find that historical records of LX Cyg show the period was fairly stable at approximately 460 d from its first measurement around JD 242 6000 to 243 9000, after which it increased to around 580 d. We note that BH Cru and LX Cyg are the two SC stars in Table A1 with the latest subtypes and longest periods. A spectrum kindly taken for us by James Bryan in 2003 confirms that LX Cyg is an SC star, but does not allow a current subclass to be determined.

We carried out a wavelet analysis of the AAVSO data, identical to that shown for BH Cru. The result is shown in Fig. 15: the axis scales are the same as in Fig. 1, to facilitate the comparison. The rate of period change in LX Cyg is very similar to that in BH Cru. The pulsation amplitude is somewhat larger and has not changed significantly, and the total change in period is larger.

A redetermination, or in several cases a first determination, of the periods of the SC/CS stars is given Appendix A. There we show that our period of VX Aql (609 d; unknown subtype) is inconsistent with an earlier determination (470 d). We have insufficient data to confirm a period change, but it seems possible that VX Aql is a third case of a SC star with an evolving period. If true, *all* SC star with periods longer than approximately 470 d show this effect. Many normal Miras with such periods also show fluctuations (Zijlstra & Bedding 2003), but limited to approximately 10 per cent in period. The SC stars show much larger changes. Even without VX Aql, a link between the C/O ratio near unity, and the unstable periods, seems likely.

5 DISCUSSION

A few Miras are known to show changing periods. The well-known case of R Hya was studied by Zijlstra et al. (2002) who find evidence for a stable period of 495 d before AD 1800, followed by a declining period, and a newly stable period of 385 dates since AD 1950. R Aql shows similar behaviour and TY Cas was recently added to the list of variable periods (Hazen & Mattei 2003). However, overall, period evolution among Miras is rare. Greaves & Howarth (2000) examined a sample of 100 Miras, and apart from the previously known case of T UMi (Gál & Szatmáry 1995; Mattei & Foster 1995; Szatmáry, Kiss & Bebesi 2003), found no further case of long-term period change. Wood (1976) studied 45 stars and found small period changes with greater than 99 per cent significance in six cases, but no large-scale evolution. Mattei & Foster (2000) performed a trend analysis of 383 long period variables using 90 yr of AAVSO data. Only 9 per cent showed evidence for trends, and of these only nine stars showed strong trends. Percy & Au (1999) analysed a sample of 391 Mira variables and found some evidence for a slow average increase in periods with time, but few or no stars with large period variability.

This suggests that over the past 50–100 yr, period evolution has only occurred in ∼1 per cent of well-observed Miras. To find a case among the seven SC/CS stars classified in the General Catalogue of Variable Stars (GCVS) as Miras with established periods is not ruled out by this rate. However, the discovery of a second case implies an overrepresentation of the SC/CS stars. The rate of occurrence of period evolution among semiregular variables is not known.

Period changes in Miras have normally been attributed to a recent thermal pulse or helium flash (Wood & Zarro 1981), this explains the

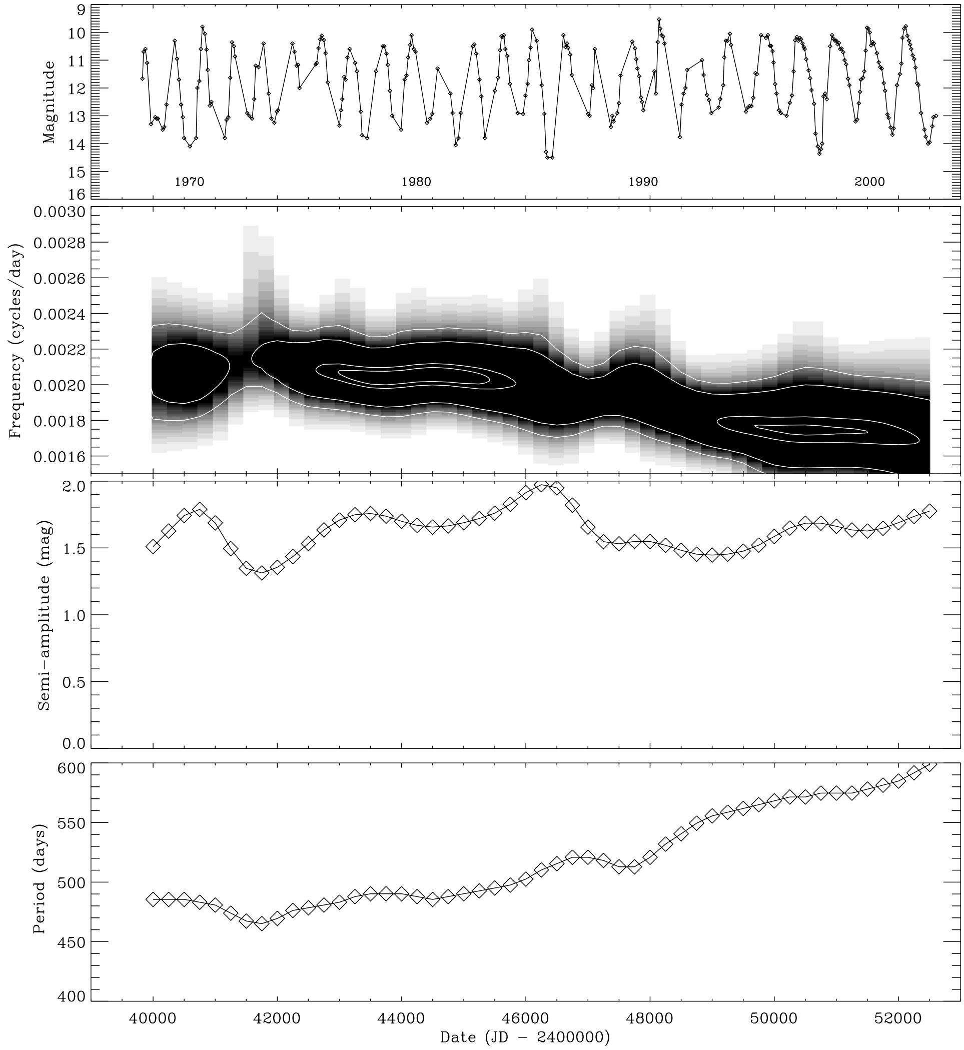

Figure 15. The wavelet analysis for LX Cyg. The lower three panels are on the same scale as Fig. 1, to facilitate comparison with BH Cru.

rarity of such objects. Fast period evolution will only occur during and immediately after the helium flash (Vassiliadis & Wood 1993). At any one time, only ∼0.1 per cent may be found at the rapid period increase. This model would therefore suggest that BH Cru is in a unique evolutionary phase, following a thermal pulse occurring during the 1960s.

However, the fact that, among the small number of SC stars, LX Cyg is also undergoing similar changes, makes the thermal-pulse explanation rather unlikely. The fact that historical records suggest recurrent period changes in BH Cru also argues against a thermal pulse. There are alternative models for period changes, predicting a non-linear instability in the Mira structure. In the case of R Hya (Zijlstra et al. 2002) those may yield a better fit to the data.

In AGB stars, the visual pulsation amplitude is largely determined by varying molecular opacities: e.g. the extreme amplitudes of oxygen-rich Miras is caused by the varying TiO and VO bands. The low molecular opacities in SC stars can explain their low pulsation amplitudes (Appendix A). However, the molecular abundances become very sensitive to small changes in the chemical equilibrium, and this may affect the pulsation amplitude. An increased pulsation will lower the effective temperature and this shifts the chemical equilibrium. This process can result in a positive feedback, which leads to larger pulsation amplitudes. Bedding et al. (2000) have suggested that a change in the amplitude can cause a period change (rather than the usually assumed reverse relation) due to non-linear effects. The positive feedback on the amplitude may thus affect the period as well, and may be a possible cause of the pulsation instability observed in BH Cru, LX Cyg and possibly VX Aql.

Finally, although we argue against a thermal pulse, we note that even if a thermal pulse did occur, the C/O ratio in BH Cru would not have changed. Carbon dredge-up following a thermal pulse does not commence until ∼250 yr after the thermal pulse (Mowlavi 1999), when the radius has returned to its pre-thermal pulse value, and is continuing to decrease. The dredge-up for the models of Mowlavi (1999) lasts for approximately 100 yr, while the period of the star is decreasing, well after the initial sharp period increase. Thus, in either case, the change from an SC to a CS star would be due to a lower temperature, and not an increase in the C/O ratio. The distinction between SC and CS stars may measure effective temperature, rather than an evolutionary progression (Stephenson 1973).

6 CONCLUSIONS

Our investigation of the evolving variable BH Cru shows an increase in its period of 25 per cent within 25 yr. The period has stabilized at approximately 540 d. The visual semi-amplitude has increased simultaneous with the period increase, up to a value of 1.25 mag. The changing period shows that the radius of the star has increased, and the temperature decreased, the latter confirmed by a slow reddening.

The spectral type of BH Cru changed simultaneously from SC to CS. Chemical equilibrium modelling, both for the photosphere and a hydrostatic atmosphere, explains this as being due to the decrease in the effective temperature. The lower temperature favours formation of C_2 and causes the fractional abundances of ZrO and YO to decrease. Our calculations explore a range of $C/O > 1$, for which oxides are still found although at reduced abundances. The distinction between SC and CS stars does not require an evolution from $C/O < 1 \longrightarrow > 1$, as sometimes is suggested, although this can also play a role. Infrared spectra suggest the possible presence of the iron-sulphide troilite in SC stars. Chemical calculations show that FeS is abundant in the photosphere, and in the absence of silicates or carbon grains, may be an important dust component.

We determined new periods for a number of SC/CS stars, including three for stars with no previously known period. One star, LX Cyg, shows a much longer period than previously determined, and is confirmed as undergoing period evolution similar to BH Cru. VX Aql also shows an inconsistency between the present period and one previously reported. Among the few Miras known with evolving periods, BH Cru was unique in showing an *increasing* period. Its time-scale for the evolution is 10 times faster than that of the well-studied case of R Hya. With LX Cyg, a second case of rapid period increase is now known.

Period changes in Miras are commonly attributed to thermal pulses. This appears unlikely in BH Cru, because other SC stars show the same type of changes. As an alternative model we suggest the possibility that a feedback between molecular opacities, pulsation amplitude and periods cause unstable periods among the long-period SC stars.

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APPENDIX A: PERIODS OF THE OTHER SC STARS

The General Catalogue of Variable Stars lists only 11 SC stars (including BH Cru) and five CS stars. These are listed in Table A1. Keenan & Boeshaar (1980) and Catchpole & Feast (1971) list a few other SC stars that the GCVS gives as carbon stars, and which perhaps should be classified as CS. In Table A1, these stars are in the third group (in italics).

Of the 16 known SC and CS stars, six have no catalogued period. We attempted to determine some of their periods, and to confirm existing periods, using new data (see below) and data from amateur data bases. New light curves and/or power spectra were determined for the six stars, as follows.

LQ Ara, AM Cen, UX Vol. Photometric observations of these three stars were obtained by one of us (VT) using CCD imaging with an unfiltered 100-mm telephoto lens. For LQ Ara, the light curve and power spectrum (Fig. A1) indicate a period of 193 d. The amplitude is low, indicating that this star is a semiregular (not a Mira, as suggested in the GCVS). For AM Cen (Fig. A2) we find a possible period of 276 d, but this requires confirmation with more data. The star UX Vol (Fig. A3) appears to be a semiregular with a period of 182 d.

GP Ori. This star is classified as a semiregular (SRb) with a period of 370 d in the GCVS. We have analysed approximately 440 visual estimates from the AAVSO and VSOLJ data bases, spread rather sparsely over the past 30 yr. The power spectrum, shown in Fig. A4,

Table A1. GCVS data for the SC and CS stars. Stars in the last section are classified as SC by Catchpole & Feast (1971) and Keenan & Boeshaar (1980): the GCVS gives these as C stars.

Name	Var. type	m_V (max)	Period (GCVS) (d)	Period (this work) (d)	Spectral type
LQ Ara	M:	10.3		193?	SC
AM Cen	LB	10.4		276?	SC
V372 Mon	SR	12.5			SC(N)
V3832 Sgr	LB:	13.4			SC
UX Vol[a]	LB:	9.2		182	SC
BH Cru	M	7.2	540	430–530	SC4.5/8-SC7/8
UY Cen	SR	9.22	115		SC
CM Cyg	M	9.3	255		SC2-S4e
LX Cyg	M	11.5	465	470–600	SC3e-S5,5e:
S Lyr	M	9.8	438	436	SCe
GP Ori	SRB	12.2	370	184, 339	C8,0J:(SC)ea
CY Cyg	LB	11.0		irregular	CS(M2p)
R CMi	M	7.25	338	337	C7,1Je(CSep)
TT Cen	M	11.5	462		CSe
FU Mon	SR	11.6	310		C8,0J(CSe)
RZ Peg	M	7.6	439	437	C9,1e(Ne)/CSe
VY Aps	SRA	9.6	152		
AM Car	SR	14.3	314		
R Ori	M	9.05	377		
RR Her	SRB	8.8	240		
W Cas	M	7.8	406		
WZ Cas	SRa	9.4	186		
VX Aql	M:			604	

[a]We note that the GCVS gives the wrong declination for this star. The correct values are $\alpha, \delta = 08^{\mathrm{h}}\,46^{\mathrm{m}}\,17\overset{\mathrm{s}}{.}6, -71^\circ\,02'\,20''$ (J2000)

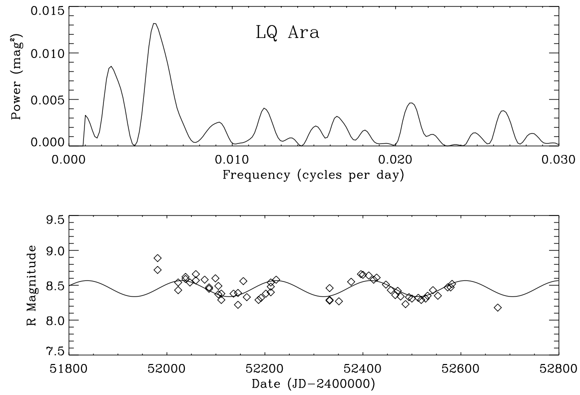

Figure A1. Power spectrum (upper panel) of the CCD light curve (lower panel) of LQ Ara; the solid curve shows the best-fitting sinusoid.

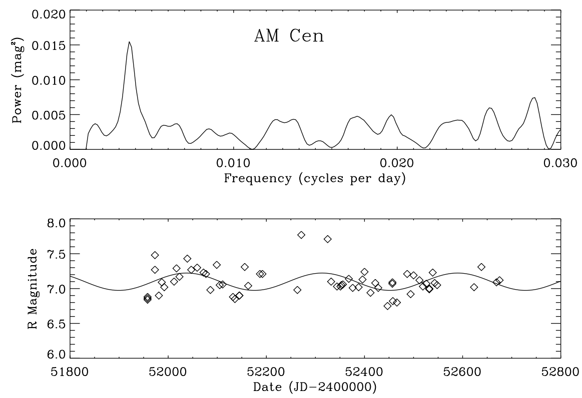

Figure A2. Power spectrum (upper panel) of the CCD light curve (lower panel) of AM Cen; the solid curve shows the best-fitting sinusoid.

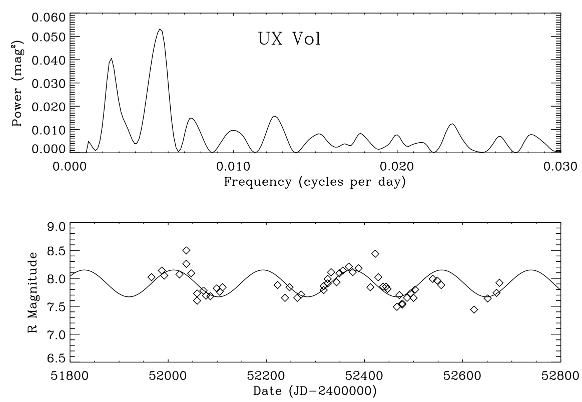

Figure A3. Power spectrum (upper panel) of the CCD light curve (lower panel) of UX Vol; the solid curve shows the best-fitting sinusoid.

confirms GP Ori as a semiregular with two periods: 184 d (0.005 43 d^{-1}) and 339 d (0.002 95 d^{-1}). The period ratio of 1.84 is typical of many semiregulars (Kiss et al. 1999). The power spectrum is somewhat complicated by yearly gaps in the data (the peak at 0.081 d^{-1} is an alias), and this is made worse by the fact that the shorter period is very close to half a year. Nevertheless, both periods seem secure. Bedding & Zijlstra (1998) showed that in double-period semiregulars, the longer period tends to agree with the Mira period–luminosity relation while the shorter period falls on the semiregular

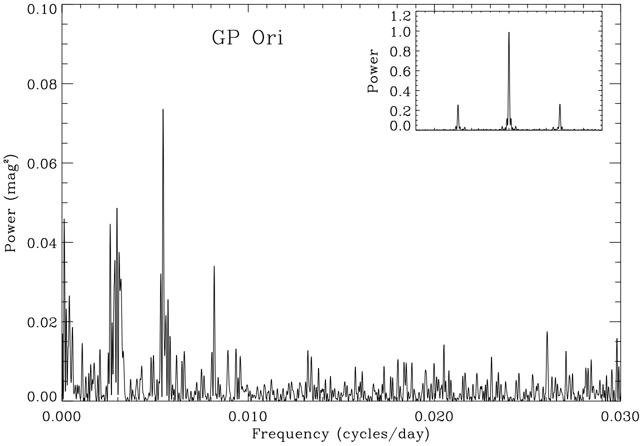

Figure A4. Power spectrum of the light curve of GP Ori showing two distinct periods. The inset shows the spectral window.

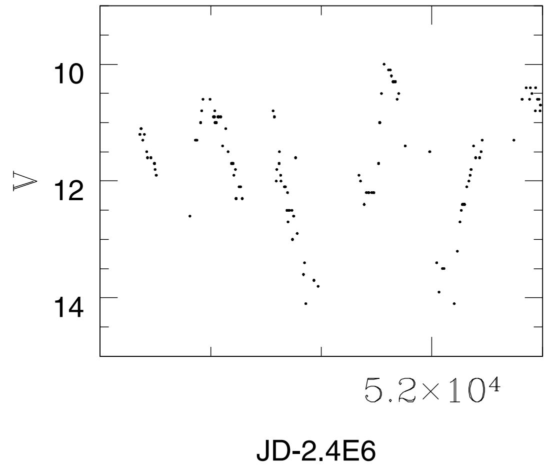

Figure A5. VSOLJ light curve of VX Aql.

sequence (sequences C and B of Wood et al. 1999). We also note that the power spectrum shows broadened envelopes that have been interpreted by Bedding (2003) as evidence for solar-like oscillations (i.e. stochastic excitation, presumably from convection).

CY Cyg. We have analysed 424 AAVSO observations from JD 243 8540 to JD 245 2653. The star seems completely irregular, and the Lb classification (which is usually based on lack of data) seems warranted.

VX Aql. This star is of particular interest because of a C/O ratio suggested to be exactly unity (Greene & Wing 1975). The GCVS lists it as a Mira but does not give a period. A VSOLJ light curve is shown in Fig. A5. The AAVSO light curve can be found on the AAVSO web site. We have analysed 86 observations from a single AAVSO observer which show the star is a Mira, with a period of 604 d and a very pronounced double maximum. Interestingly, Wyckoff & Wehinger (1976) adopted a period of ∼470 d, which they attributed to Kurochkin (1958). It seems possible that VX Aql is another example of an SC/CS star that has shown a large period increase.

RZ Peg, S Lyr, R CMi. For each of these stars, visual observations from AAVSO, VSOLJ and AFOEV data bases show them to be Miras and confirm the periods listed in the GCVS and in Mattei & Foster (2000). The data go back 80–90 yr, over which time the periods are all stable.

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