Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **407,** 1070–1077 (2010) doi:10.1111/j.1365-2966.2010.16886.x

The dust-free symbiotic Mira K4−46 = LL Cas

U. Munari,[1]★ A. Siviero,[1] S. Dallaporta[2] and A. Frigo[2]

[1]*INAF Astronomical Observatory of Padova, 36012 Asiago (VI), Italy*
[2]*ANS Collaboration, c/o Osservatorio Astronomico, via dell'Osservatorio 8, 36012 Asiago (VI), Italy*

Accepted 2010 April 21. Received 2010 April 20; in original form 2010 March 22

ABSTRACT

Accurate BVR_CI_C light and colour curves of the Mira variable in the dust-free symbiotic system K4−46 are presented and discussed. They cover several consecutive pulsations cycles. The Mira mean period is 284.2 d, the reddening sums to $E(B-V) = 0.35$ and the distance is 10 kpc. Absolute spectrophotometry at both maximum and minimum brightness of the Mira is presented. The rich emission line and continuum spectrum of the H II region ionized by the hard radiation of the white dwarf dominates at Mira minimum. From its photoionization analysis, it is found that the H II region extends to a radius of 210 au, has a mass 1.8×10^{-4} M$_\odot$ and it is ionized by a white dwarf of 158 000 K temperature and 0.06 R$_\odot$ radius, stably burning hydrogen at its surface. The derived [Fe/H] = −0.45 well match the ambient metallicity expected at K4−46 at its 15 kpc galactocentric distance, and the overabundances in N, Ne and He are those expected if the H II region is fed by the wind of the Mira and polluted by nuclearly processed material lost by the white dwarf companion.

Key words: stars: AGB and post-AGB – binaries: symbiotic – stars: individual: LL Cas.

1 INTRODUCTION

Symbiotic binaries containing a Mira variable are relevant astrophysical objects for several reasons, including (i) their white dwarfs are typically very bright, go through stable H-burning of the accreted material and experience outbursts lasting for centuries (Munari 1997; Sokoloski 2003); (ii) the mean radius of the pulsating Mira must be smaller than its Roche lobe radius and therefore the white dwarf companion accretes mainly from wind; (iii) obscuration events are observed with a frequency higher than in field Miras (Whitelock 2003). This seems related to the binary nature of symbiotic Miras. When passing at inferior conjunction, the Mira could be eclipsed by the dust forming and surviving in its own shadow (Whitelock 1987). However, the high fraction of field (and presumably single) carbon Miras showing obscuration events suggests that also other mechanisms could contribute to their occurrence (Whitelock et al. 2006); (iv) they harbour bipolar, toroidal and hourglass-like circumstellar nebulae that bear much in common with the shape of axisymmetric planetary nebulae (Corradi et al. 2001; Santander-Garcia et al. 2007), and could share a common formation mechanism.

The majority of symbiotic Miras have been discovered and initially studied as bona fide planetary nebulae. Their optical spectra are in fact generally dominated by the emission of the ionized circumstellar material (Allen 1984; Munari & Zwitter 2002). The Mira components are frequently embedded in a thick dust cocoon that do not extend enough to engulf also the H II region surrounding their white dwarf companion (Allen 1983). Therefore, detection and direct observability of the Mira is usually limited to infrared wavelengths. In a few systems, however, the extinction from dust is low or absent and the emission from the ionized gas is weak enough to allow direct observation of the Mira even at optical wavelengths. K4−46 is such a system.

K4−46 was discovered as a point-like possible planetary nebula by Kohoutek (1965) on 103a-E+RG1 objective prism plates obtained with the Hamburg 80/120 f-3 Schmidt telescope. As such it entered the catalogue of Galactic planetary nebulae of Perek & Kohoutek (1967) as PK 108−05. It was detected as a weak radio emitter at 2 cm by Rubin (1970). Allen (1974) obtained *JHK* infrared photometry of K4−46 that indicated the presence of a late-type giant in the system, and consequently it was inserted among misclassified planetary nebulae by Kohoutek (1978). The misclassified PN nature of K4−46 was confirmed by Sabbadin, Falomo & Ortolani (1987, hereafter S87) from a low-resolution 4500–6800 Å spectrum that displayed TiO absorption bands and superimposed weak Hα and Hβ in emission. No other obvious emission lines were present (He II and [O III] in particular), and S87 concluded that K4−46 was an Me star with no clear evidence of a symbiotic nature.

The identity of K4−46 with the variable star LL Cas was pointed out by Bond (1976). LL Cas was discovered by Götz, Huth & Hoffmeister (1957) as a long period variable, varying from m_{pg} = 15.3 at maximum to fainter than 17 at minimum. They provided only scanty information in the form of six epochs of maximum

★E-mail: ulisse.munari@oapd.inaf.it

Table 1. Our BVR_CI_C photometry of K4−46. This table is published in its entirety in the electronic version of the paper (see Supporting Information). A portion is shown here for guidance regarding its form and content.

HJD	Date	V	$B-V$	$V-R_C$	$V-I_C$
245 5139.365	2009 11 03.865	14.007	2.002	1.526	3.334
245 5142.390	2009 11 06.890	13.971	2.130	1.459	3.273
245 5146.378	2009 11 10.878	13.990	2.036	1.506	3.321
245 5153.341	2009 11 17.841	14.025	1.993	1.541	3.400
245 5156.366	2009 11 20.866	14.028	2.029	1.548	3.399
245 5167.261	2009 12 01.761	14.121	2.091	1.588	3.510
245 5176.309	2009 12 10.809	14.286	1.950	1.634	3.638
245 5180.338	2009 12 14.838	14.362	1.922	1.652	3.708

brightness and the following ephemeris $m_{\rm pg}(\max) = 242\,7957 + 141 \times E$, which is the only information listed in the General Catalogue of Variable Stars.[1]

Kondratyeva (1992, hereafter K92) reported about 19 photometric observations in photographic V band obtained between 1986 and 1991, which supported a variability period twice longer that given by Götz et al. (1957). K92 provided the following ephemeris: $V(\max) = 24\,27957 + 286.6 \times E$. Based on new V-band observations extending from 1991 September to 2006 September, Kondratyeva & Denissyuk (2008, hereafter KD08) revised the ephemeris to $V(\max) = 242\,7957 + 283.02 \times E$.

K92 obtained low-resolution photographic spectra, both at maximum and at minimum brightness. The spectra confirm the presence of TiO absorption bands and show an emission-line spectrum far richer than reported by S87. K92 quoted the presence of Balmer and other emission lines distributed over a wide range of ionization, from Mg I 4570 and C II 4267 to [Fe VII] 4892 and Ne VI 4718, and remarked how the equivalent width of the emission lines was larger when LL Cas was at minimum optical brightness. The variability with time of the relative strengths of emission lines was noted by KD08. Based on K92 results, K4−46 entered the catalogue of symbiotic stars compiled by Belczynski et al. (2000).

In this paper we present accurate CCD photometry in the BVR_CI_C bands, tightly covering some consecutive pulsation cycles of the Mira. We also provide absolutely fluxed spectra, obtained when the Mira was both at maximum and minimum brightness, which allow us to study the ionizing source and the circumstellar nebula.

2 OBSERVATIONS

2.1 Photometry

BVR_CI_C CCD photometric observations were obtained with a 0.30-m Meade RCX-400 f/8 Schmidt-Cassegrain telescope located in Cembra (Trento, Italy). They are listed in Table 1 (full version available electronic only). The CCD was a SBIG ST-9, 512 × 512 array, 20 μm pixels ≡ 1.72 arcsec pixel^{-1}, with a field of view of 13 × 13 arcmin^2. The B filter was from Omega and the VR_CI_C filters from Custom Scientific.

The observations were calibrated on the $UBVR_CI_C$ photometric sequence published by Henden & Munari (2001), augmented by inclusion of the three additional field stars given in Table 2 for a wider leverage on colour equations. The average Poissonian error of the V data goes from 0.005 mag at maximum brightness to 0.012 mag at minimum, and from 0.006 to 0.013 mag for colours. The typical rms of the standard stars from the calibrating colour equations is 0.011 mag. To ensure this high accuracy, the average V-band total exposure time per single data point ranged from 500 s at maximum brightness to 3 h at minimum.

[1] http://www.sai.msu.su/groups/cluster/gcvs/gcvs/

Table 2. Field stars used in addition to those given by Henden & Munari (2001) in the calibration of photometric data of K4−46 given in Table 1.

$\alpha_{\rm J2000}$	$\delta_{\rm J2000}$	V	$B-V$	$U-B$	$V-R_C$	$V-I_C$
347.285889	54.797287	13.992	1.314	1.059	0.724	0.661
		±0.016	±0.013	±0.009	±0.037	±0.014
347.305939	54.754402	14.413	1.313	1.033	0.730	0.676
		±0.007	±0.006	±0.002	±0.027	±0.009
347.220337	54.786671	14.932	1.410	1.349	0.778	0.697
		±0.013	±0.009	±0.009	±0.078	±0.016

Our observations cover three distinct intervals of time: the first one, lasted from 2005 November 22 to 2006 March 7, the second from 2007 January 13 to 2007 January15 and the third one from 2007 September 1 uninterrupted till 2010 March 14. The overall light curve is presented in Fig. 1.

2.2 Spectroscopy

A wide wavelength range (3270–7960 Å), low-resolution (2.30 Å pixel^{-1}) spectrum of K4−46 was obtained on 2007 December 28 (close to minimum Mira brightness) with the 1.22-m telescope operated in Asiago by the Department of Astronomy of the University of Padova. A total exposure of 4.8 h was accumulated with the B&C spectrograph, 300 ln/mm grating and ANDOR iDus 440A CCD camera, equipped with a EEV 42-10BU back illuminated chip, 2048 × 512 pixels of 13.5-μm size. The spectrograph slit was 2.0-arcsec wide and aligned with the parallactic angle. The faintness and very red colours of K4−46 prevented from recording the spectrum below 3800 Å. Some fringing at $\lambda \geq 7400$ Å remained uncorrected by flat-fielding procedure.

A similarly wide wavelength range (3525–7810 Å), low-resolution (4.24 Å pixel^{-1}) spectrum of K4−46 was obtained on 2009 October 14 (close to maximum Mira brightness) with the 1.82-m telescope operated in Asiago by the INAF Astronomical Observatory of Padova and equipped with the Asiago Faint Object Spectrograph and Camera (AFOSC) imager+spectrograph and a 300 ln/mm grism. The detector was a Tektronix TK1024 thinned CCD, 1024 × 1024 array and 24-μm pixel. The slit, aligned with the parallactic angle had a width of 1.26 arcsec.

Observations on both dates of several spectrophotometric standard stars allowed calibration of the K4−46 spectra into absolute fluxes. They are quite accurate because integrating on the spectra the B, V and R_C bands provides values within a few hundreds of a magnitude of contemporaneous CCD photometry in Table 1. The spectra are presented in Fig. 3, and Table 3 lists the integrated flux of the emission lines measured on the 2007 December 28 spectrum.

3 RESULTS

3.1 The Mira pulsation

The light curve in Fig. 1 confirms the presence of a Mira in the system. As typical for Mira variables, the shape of pulsation light curve and the time of maximum brightness slightly change from one cycle to the next. Combining our data with those of earlier cycles covered by K92 and KD08, the following ephemeris is the

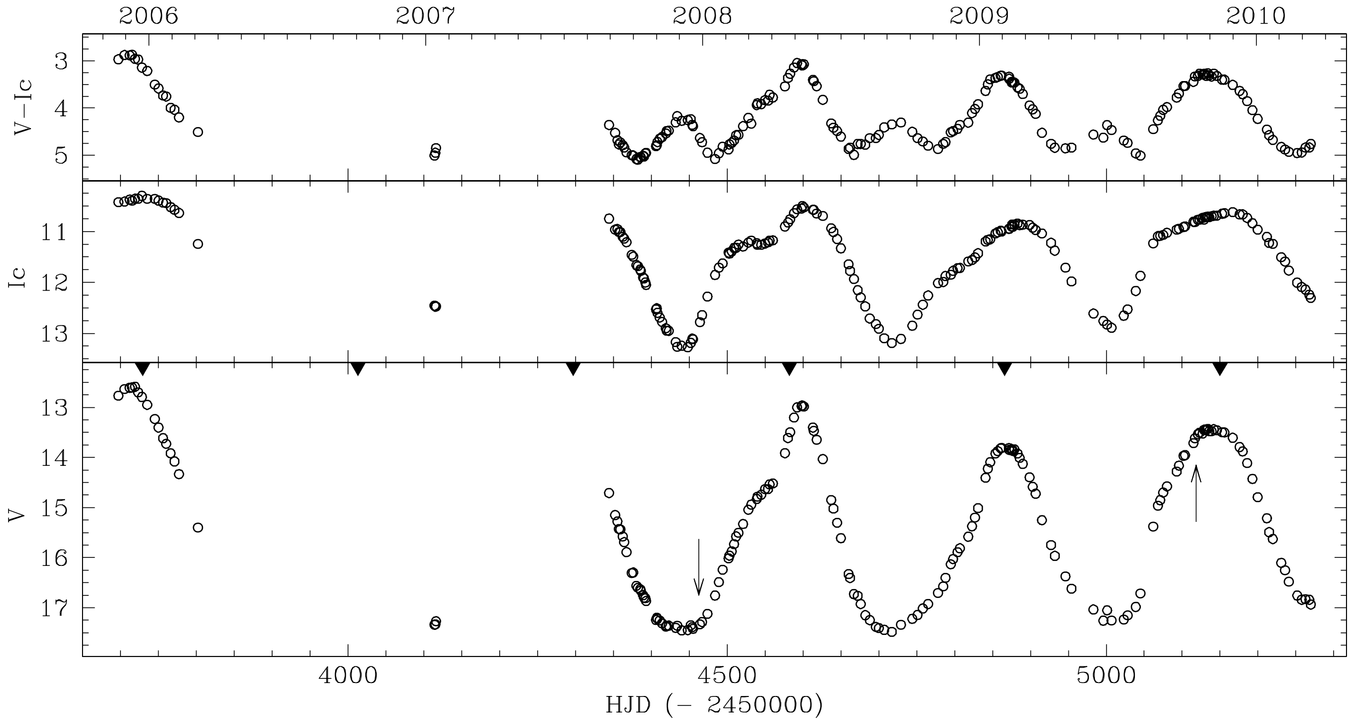

Figure 1. Light and colour curve of K4−46 from our observations in Table 1, extending from 2005 November 22 to 2010 March 15.

one better fitting the whole set of V-band data:

$$V(\text{max}) = 245\,5150 + 284.2 \times E. \quad (1)$$

The times of maxima are marked as triangles on the V-band panel of Fig. 1.

Comparing the V and I_C light curves in Fig. 1, it is evident how the maximum I_C brightness comes ∼27 d past maximum in V band. This is a common behaviour of Miras, as first discovered by Hetzler (1936), who estimated in 10 per cent of the period the mean delay between maxima at wavelengths roughly comparable with those of modern I_C and V bands. The delay further increases going into the infrared, as first shown by Pettit & Nicholson (1933). They found the delay between maxima at visual and bolometric effective wavelengths (essentially the flux integrated over the J, H and K bands) to amount to 14 per cent of the period.

3.2 Intrinsic Mira variability

Mira variables change their effective temperature along the pulsation cycle: the surface is hottest and the colours bluer around maximum brightness, while it is coolest and the colours redder around minimum brightness (cf. Hoffmeister, Richter & Wenzel 1985, and references therein). The light and colour curves of K4−46 in Fig. 1 follow this pattern at maximum brightness, but not around minimum.

The reason is the presence of the circumstellar ionized nebula. As Fig. 3 shows, while the nebula provides a negligible contribution to the V band at the time of Mira maximum, it becomes the dominant source when the Mira is at minimum. Only in the I_C band the Mira remains (by far) the dominant emitter even at minimum brightness. Thus, the presence of the intrinsically bluer emission from the ionized circumstellar nebula both (i) reduces the observed amplitude of variability of the Mira at the bluer wavelengths, and (ii) affect the optical colours of the system when the Mira is at its faintest state.

To evaluate the effect, Fig. 2 (left-hand panels) plots the complete 284.2 d pulsation cycle (from 2007 September 1 to 2008 June 9) centred on the time of acquisition of the 2007 December 28 spectrum presented in Fig. 3 (when the Mira was close to minimum brightness). The observed amplitudes are $\Delta V = 3.96$ (from $V = 17.512$ to 13.553), $\Delta R_C = 4.07$ (from $R_C = 16.157$ to 12.083), $\Delta I_C = 2.77$ (from $I_C = 13.270$ to 10.503), $\Delta(V - R_C) = 0.87$ (from +2.145 to +1.271), $\Delta(V - I_C) = 2.05$ (from +5.096 to +3.046) and $\Delta(R_C - I_C) = 1.43$ (from +2.992 to +1.563).

The photoionization modelling presented in Section 4 shows that the ionized circumstellar nebula of K4−46, if taken alone, would shine at $V = 17.65$, $R_C = 16.87$, $I_C = 17.10$. Subtracting its contribution from the recorded photometry, produces the light and colour curves on the right-hand panels of Fig. 2. They represent the pulsation of the Mira cleaned from the contribution of the ionized circumstellar nebula. The shape of the light and colour curves is now what expected from a normal Mira, and the anomalous colour reversal at minimum brightness has disappeared. The intrinsic light-curve amplitudes are $\Delta V = 6.24$, $\Delta R_C = 4.72$, $\Delta I_C = 2.80$. The ratio $\Delta V/\Delta I_C$ is 2.2, in excellent agreement with the value ≈2.1 established by Hetzler (1936) from a survey of a large number of field Miras.

3.3 Reddening

The intrinsic $B - V$ colour of M giants does not depend from the spectral type and hence the effective temperature, as illustrated by Johnson (1966) and Lee (1970), who provide $\langle (B - V)_\circ \rangle = +1.61$ as the mean intrinsic colour of M giants. The $B - V$ data in Table 1, obtained when the Mira was close to maximum brightness and the interference by the emission nebula negligible, provide a median value $\langle (B - V) \rangle = +1.95$. It suggests a reddening $E(B - V) = 0.34$ affecting K4−46.

Table 3. Emission lines measured on the K4−46 spectrum for 2007 December 28 presented in Fig. 3. The third column lists the integrated flux in erg cm^{-2} s^{-1}. The fourth column gives the fluxes corrected for the $E(B-V) = 0.35$ mag reddening and expressed relative to $F(\mathrm{H}\beta) = 100$.

Ident	λ (Å)	Obs. flux	$\left(\frac{F(\lambda)}{F(\mathrm{H}\beta)}\right)_\circ$
He I	3838	4.917E-14	89
[Ne III]	3869	2.986E-13	539
H8 + He I	3889	9.922E-14	178
[Ne III]	3967	1.045E-13	183
	4070	2.245E-14	38
Hδ + N III	4101	6.234E-14	105
Hγ	4340	4.973E-14	79
[O III]	4363	8.630E-14	137
[Fe II]	4416	9.106E-15	14
He I	4471	9.739E-15	15
He II	4686	2.982E-14	43
Hβ	4861	7.290E-14	100
He I	4922	2.119E-15	3
[O III]	4959	6.114E-14	82
[O III]	5007	1.774E-13	234
	5039	2.526E-15	3
[Fe VII]	5158	6.331E-15	8
[Fe VI]	5177	2.570E-15	3
He II	5412	2.978E-15	4
He I	5876	2.585E-14	28
[Fe VII]	6086	4.250E-15	4
[O I]	6300	6.096E-15	6
	6312	3.298E-15	3
[O I]	6364	1.895E-15	2
Hα	6563	5.332E-13	506
[N II]	6584	1.443E-14	14
He I	6678	6.596E-15	6
He I	7065	2.302E-14	20
[Ar III]	7136	4.045E-15	4
[Fe II]	7155	3.233E-15	3
[Fe II]	7172	3.034E-15	3

Feast, Whitelock & Carter (1990, see also Tammann, Sandage & Yahil 1979) proposed the following expression for the reddening as function of distance and Galactic coordinates: $E(B-V) = 0.032(\mathrm{cosec}\,|b| - 1)[1 - \exp(-10r \sin |b|)]$, where r is the distance in kpc and b is the Galactic latitude. For K4−46 it provides $E(B-V) = +0.32$.

Neckel & Klare (1980) reddening maps suggest a total extinction $E(B-V) \sim 0.28$ toward the K4−46 direction. Arenou, Grenon & Gomez (1992) reddening maps provide $E(B-V) = 0.41$ for K4−46 and those of Drimmel et al. (2003) give $E(B-V) = 0.32$.

The straight average of these statistical determinations of the reddening affecting K4−46 is

$$E(B-V) = 0.35 \tag{2}$$

and it will be adopted in this paper.

3.4 Distance

Whitelock, Feast & van Leeuwen (2008) have re-examined the period–luminosity relation of Mira variables taking advantage of the new reduction of *Hipparcos* observations. They found for Galactic, O-rich Miras the relation $M_K = \rho[\lg P - 2.38] + \delta$, where $\rho = -3.51 \pm 0.20$ and $\delta = -7.25 \pm 0.07$, with the zero-point independent from metallicity.

There are only two infrared measurements available for K4−46, one from Allen (1974) and the other from Two Micron All Sky Survey (2MASS). The latter reports $K_s = 7.13 \pm 0.02$ for JD 245 1173 (Phillips 2007), which corresponds to pulsation phase 0.00 according to ephemeris (1). The pulsation amplitude for Miras of periods similar to K4−46 is $\Delta K \approx 0.75$ mag according to Whitelock, Feast & Catchpole (1991). This suggests a mean brightness $\langle K_s \rangle \approx 7.5$ for K4−46. Allen (1974) reports $K = 7.55$ for K4−46 but does not specify the corresponding observing date. The agreement of the two measurements supports assuming $K = 7.53$ mag as the mean K-band brightness of LL Cas. The Whitelock et al. (2008) period–luminosity relation then provides

$$d \sim 10\,\mathrm{kpc} \tag{3}$$

as the distance to K 4-46, where we adopted $A_K = 0.15$. It derives from the reddening $E(B-V) = 0.35$ and the $A(\lambda)/E(B-V) = 0.424$ relation calibrated by Fiorucci & Munari (2003) for M giants observed in the South African Astronomical Observatory (SAAO) infrared system and obeying the standard $R_V = 3.1$ extinction law. This distance corresponds to a height above the Galactic equatorial plane of $z = 880$ pc and a galactocentric distance $R = 15$ kpc.

3.5 The symbiotic nature of K4−46

The spectrum of K4−46 at Mira minimum presented in Fig. 3 firmly confirms the symbiotic binary nature of K4−46: simultaneous presence of a cool giant (TiO absorption bands emerging in the red) and high-ionization conditions (He II and Fe VII emission lines) tracing the presence of a very hot companion. These emission lines are much harder to see at Mira maximum brightness, when the underlying Miras continuum is 300 times brighter. The spectrum of K4−46 obtained at Mira minimum and presented in Fig. 3, offers therefore the best opportunity for a detailed study of the hot component and circumstellar material in K4−46, which will be carried out in the next section.

S87 did not report what was the observing date of their K4−46 spectrum. Inspection of the original log-books of the B&C spectrograph at the Asiago 1.82-m telescope fix it to 1985 October 11, 23:00 UT (JD 244 6350.46), which corresponds to pulsation phase 0.96 according to equation (1), i.e. close to maximum Mira brightness. This well agrees with the fact that S87 observed an M-type absorption spectrum over the whole optical range, with just weak Hα and Hβ in emission. Interestingly, S87 spectrum did not show [O III] 5007 Å in emission. In our spectrum for Mira at maximum brightness in Fig. 3, [O III] 5007 is instead stronger than Hβ. The absence of [O III] 5007 in the S87 spectrum indicates that the circumstellar nebula changes significantly with time. This conclusion is reinforced by the comparison of our spectra in Fig. 3, with those taken by K92 at similar pulsation phases.

3.6 Comparison with other symbiotic Miras

The Mira in K4−46 is different from the bulk of other symbiotic Miras for its short pulsation period, the bluer infrared colours and lack of circumstellar dust.

The 284-d pulsation period for K4−46 and the 280-d period of BI Cru (Whitelock et al. 1983), albeit close to the mean period for field Miras (cf Whitelock 2003, her fig. 2), are the shortest known for symbiotic Miras.

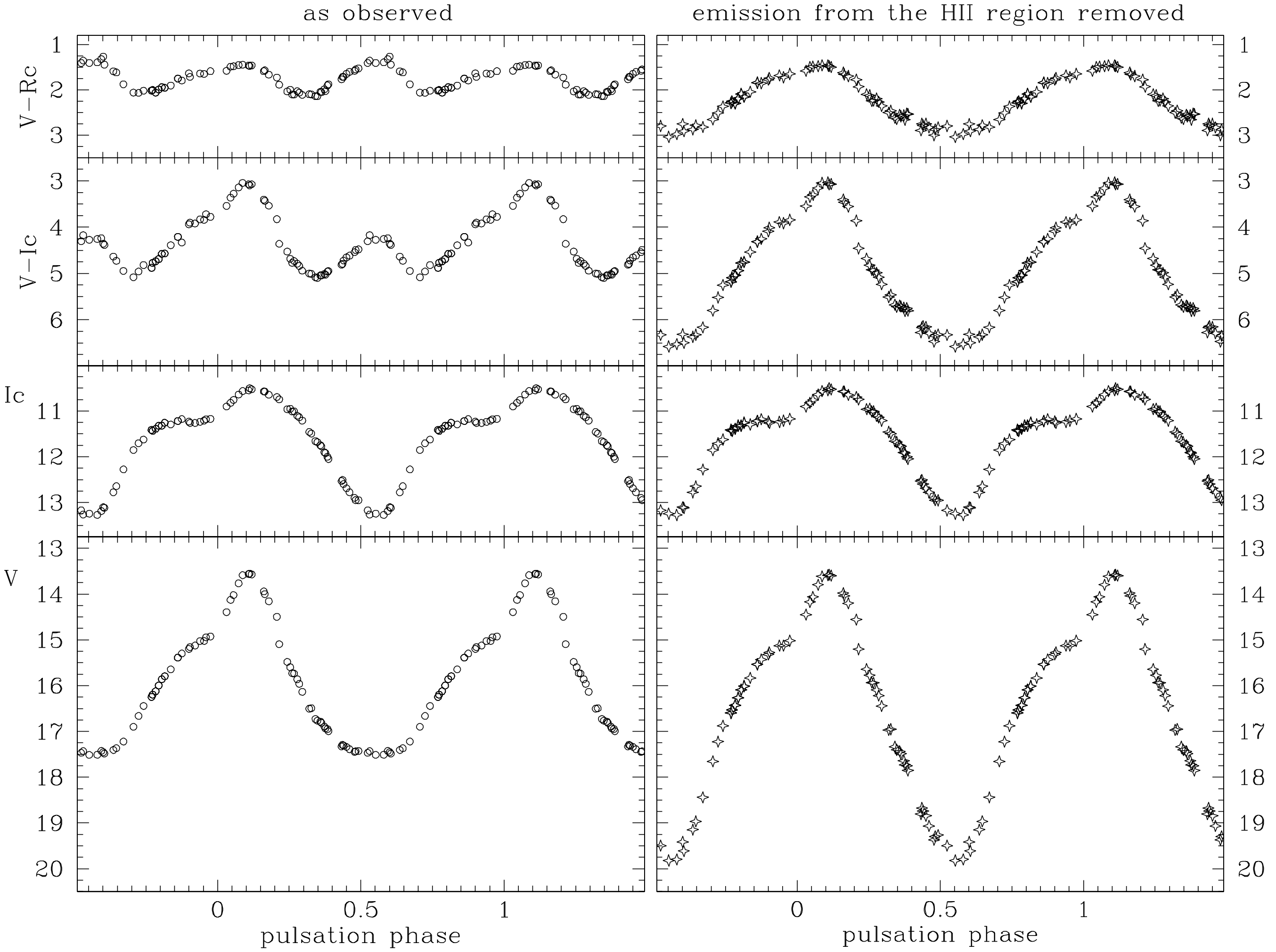

Figure 2. Light and colour evolution of K4−46 phased according to the pulsation ephemeris equation (1). Data from 2007 September 1 to 2008 June 9 are used (covering exactly one pulsation cycle). Left-hand panels: data as recorded during observations. Right-hand panels: the same data after the contribution of the H II circumstellar region has been subtracted (see Section 3.2 for details).

For a Mira to be recognized as a symbiotic one, its white dwarf companion has to be hot and bright enough to ionize a significant fraction of the Mira's wind. The emission lines and continuum from the ionized gas must turn bright enough to be recognized on optical spectra against the strong Mira's background spectrum. A higher mass loss from the Mira favours a higher accretion, and thus a brighter white dwarf companion and an easier detection as a symbiotic system. The mass-loss rate increases with the pulsation period, and consequently long-period Miras are favoured to show up symbiotic characteristics if they have a white dwarf companion at a suitable distance to accrete generously from their wind. This could explain the paucity of symbiotic Miras of short pulsation period. The low-mass loss of the Mira in K4−46 could also be the reason for the absence of significant circumstellar dust.

Further investigation of the properties of the Mira in K4−46 appears appropriate. The infrared light curves are available for essentially all symbiotic Miras, and obtaining one for K4−46 would allow a better comparison. Infrared spectra over the J, H, K bands and search for optically thin, cold dust at L (and longer wavelength bands) would also be beneficial.

4 PHOTOIONIZATION ANALYSIS

A photoionization analysis of the emission-line spectrum of K4−46 presented in Fig. 3 (top panel), has been performed with CLOUDY code (Ferland et al. 1998). Table 3 lists the integrated flux of the observed emission lines, and their reddening corrected flux relative to Hβ. The results of the CLOUDY modelling are given in Table 4, and the corresponding chemical mass-fractions are presented in Table 5.

We assumed a spherical nebula with a constant gas density. We explored other density profiles ($\rho(r) \propto r^n$, with $n = -1$, -2 and -3), but always obtained a worse match with observations. The ionizing stellar source was assumed to radiate as a blackbody. The inner and outer radii for the ionized shell ($r^{\rm in}_{\rm neb}$ and $r^{\rm out}_{\rm neb}$), and the ratio of the filled to vacuum volumes in the ejecta (ξ) were treated as free parameters. Various metallicities were explored, and we adopted [M/H] $= -0.6$ as the one providing the best results. Only the abundances of chemical elements with observed lines were allowed to change with respect to the solar partition.

The actual shape of the nebula in K4−46 could possibly be far from spherically symmetric. However, no high-resolution imaging

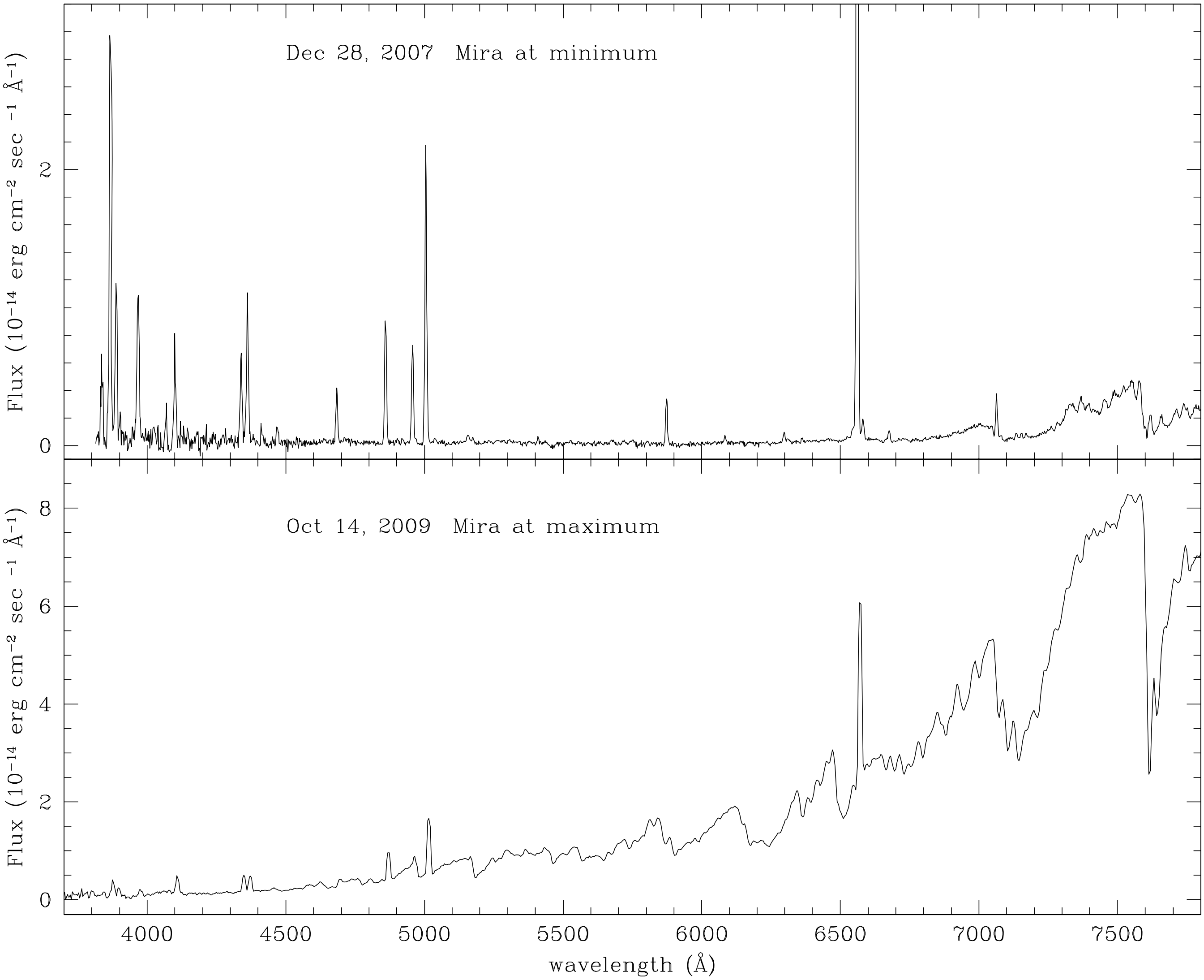

Figure 3. Absolutely fluxed spectra of K4−46 for 2007 December 28, when the Mira was at minimum brightness, and for 2009 October 14, when the Mira was close to maximum brightness.

or other information is available to drive an alternative approach. We also assumed the ionizing source to be at the centre of the nebula. While it is true that the nebula originates from the wind of the Mira, and the white dwarf orbits around it, nevertheless the orbital periods believed to characterize symbiotic Miras are of the order of a decade (e.g. Whitelock 1987, 2003). Assuming this to be the case for K4−46 too, the orbital separation would be such a small fraction of the nebula overall dimension that assuming the white dwarf seating at its centre appears appropriate. We also assumed that conditions for photoionization equilibrium apply to the nebula. The nebula reacts on the recombination time-scale to changes of the input source (e.g. Binette et al. 2003). The recombination time-scale of hydrogen, averaged over the whole nebula, is $t_{\rm rec} \sim 8$ d. We therefore assumed that if the white dwarf output is variable, it either varies on time-scale much shorter than $t_{\rm rec}$ (so that the nebula wash out the changes) or much longer than $t_{\rm rec}$ (so that the nebula is always in equilibrium with the instantaneous radiation field of the white dwarf).

The resulting iron abundance in K4−46 is [Fe/H] = −0.45, which matches the ambient metallicity for the Galactic disc at the object galactocentric distance. The ambient metallicity depends from the type and age of the population used to trace it (cepheids, planetary nebulae, open clusters, etc.). At $R \sim 15$ kpc, [Fe/H] = −0.3 was found by Luck et al. (2003), [Fe/H] = −0.45 by Chen, Hou & Wang (2003), [Fe/H] = −0.55 by Friel et al. (2002) and [Fe/H] = −0.7 by Carraro, Ng & Portinari (1998) and Pedicelli et al. (2009).

The total mass in the ionized nebula is

$$M_{\rm shell} = \frac{\xi}{X} \int_{r_{\rm in}}^{r_{\rm out}} 4\pi r^2 \rho({\rm H})\,{\rm d}r = 1.8 \times 10^{-4}\,{\rm M}_{\odot}, \qquad (4)$$

where ρ(H) is the constant hydrogen density. It indicates ionization of a substantial fraction of the Mira's wind. In fact, assuming the Mira is loosing mass at a rate $\mathrm{d}M/\mathrm{d}t \approx 5 \times 10^{-6}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ and with a wind velocity $\sim$20 km s^{-1}, the mass in the wind within 210 au from the Mira (corresponding to the size of the ionized shell) is $2.5 \times 10^{-4}\,{\rm M}_{\odot}$.

The ionizing source has a radius $0.06\,{\rm R}_{\odot}$, a temperature 158 000 K and a luminosity $2000\,{\rm L}_{\odot}$. These values well correspond to those of the evolutionary track of a $0.60\,{\rm M}_{\odot}$ nucleus of a planetary nebula at the time it reaches the hottest temperatures (Schonberner 1989), right before stopping burning the residual

Table 4. Parameters of the CLOUDY model best fitting the de-reddened emission line ratio of Table 3. From top to bottom: temperature and radius of the central blackbody source, inner and outer radii of the emitting shell, hydrogen density at inner and outer radii, electronic density at the inner radius, ratio of the filled to vacuum volumes and element abundances relative to solar partition.

$T_{\rm BB}^{\rm eff}$	158 000 K
$R_{\rm BB}$	0.060 $R_{\odot}$
$L_{\rm BB}$	2000 $L_{\odot}$
$r_{\rm neb}^{\rm in}$	0.5 au
$r_{\rm neb}^{\rm out}$	210 au
log ρ(H)	6.61 cm^{-3}
ξ	0.17
[M/H]	−0.6
He	3.0×
Ne	8.3×
N	44×
O	1.86×
Ar	0.72×
Fe	1.42×

Table 5. Mass-fraction abundances of measured elements in the emission nebula of K4−46 and, for reference, in the Sun.

	Mass-fractions	
	LL Cas	Sun
X	0.450	0.704
Y	0.537	0.279
Z	0.048	0.017
N	0.025	9.1(−4)
O	9.9(−3)	8.3(−3)
Ne	8.8(−3)	1.7(−3)
Ar	5.1(−5)	1.1(−4)
Fe	1.1(−3)	1.3(−3)

hydrogen at the surface and turn on to the cooling path of white dwarfs. This suggests that the ionizing source in K4−46 is a white dwarf experiencing stable H-burning conditions at its surface of the material accreted from the Mira companion. In fact, a luminosity 2000 $L_{\odot}$ would correspond to the potential energy liberated by an accretion rate $dM/dt \approx 1.3 \times 10^{-6}\,M_{\odot}\,yr^{-1}$ on a 0.6 $M_{\odot}$ white dwarf. It would imply that essentially all the material lost via wind from the Mira is funnelled toward the white dwarf companion and accreted on to it. On the other hand, stable hydrogen burning on the white dwarf surface would require an accretion rate of only $dM/dt \approx 4.1 \times 10^{-8}\,M_{\odot}\,yr^{-1}$ to account for the observed luminosity (at the hydrogen mass fraction of Table 5), corresponding to accrete only a few per cent of the mass lost via wind from the Mira companion. It is worth to note that an accretion rate $dM/dt \approx 4.1 \times 10^{-8}\,M_{\odot}\,yr^{-1}$ is exactly the amount required by theoretical model for stable hydrogen burning to occur on the surface of a 0.60 $M_{\odot}$ white dwarf (cf. Kenyon 1986 and references therein).

A mass of 0.6 $M_{\odot}$ for the white dwarf in K4−46 corresponds to a progenitor mass of the order of 1.0 $M_{\odot}$ (Schonberner 1989). This sets a constrain on the mass of the Mira companion, the less evolved of the two stars in K4−46. Even accounting generously for the uncertainties and mass transfer during the final evolution of the progenitor of the white dwarf, the Mira cannot arguably be more massive than ∼1.5 $M_{\odot}$. The chemical abundance ratios observed in Galactic M giants of small mass and in planetary nebulae are $0.06 \leq N/O \leq 2.5$ and $0.075 \leq He/H \leq 0.160$ (e.g. Nussbaumer et al. 1988; de Freitas-Pacheco & Costa 1992; Costa & de Freitas-Pacheco 1994, and references therein), with both ratios increasing with increasing initial mass. In K4−46 we derive larger ratios, namely N/O = 3.1 and He/H = 0.3. They could indicate that material originating from the white dwarf has been mixed into the nebula via quiescent wind or ejection episodes similar to nova eruptions. In fact, novae ejecta are observed to be heavily enriched in He and N, and deprived in H (cf. Gerhz et al. 1998), and stable hydrogen burning on the white dwarf is expected to produce similar trends. It is worth noticing that among the many symbiotic stars surveyed by Luna & Costa (2005), only Hen 3−1591 with N/O = 3.3 and Hen 2−171 with N/O = 2.4 show a nitrogen enhancement comparable to that observed in K4−46.

Luna & Costa (2005) give as mean values for symbiotic stars $\langle Ne/O \rangle = 0.12$ ($\sigma = 0.05$) and $\langle Ar/O \rangle = 0.068$ ($\sigma = 0.144$), while for K4−46 we find Ne/O = 0.67 and Ar/O = 0.0013 and for the Sun it is Ne/O = 0.15 and Ar/O = 0.0033 (Asplund, Grevesse & Sauval 2005). While Ar is normal, Ne appears enhanced by a factor of ∼5/6 in K4−46. This Ne excess does not originate from the white dwarf because neither stable hydrogen burning nor nova outburst synthesizes Ne. The huge Ne enhancement sometimes observed in novae (e.g. Gerhz et al. 1998) is due to dredge-up and mixing into the ejecta of Ne present in the white dwarf interior, which was produced during normal evolution of a massive progenitor (Gil-Pons et al. 2003; Hernanz 2005). This is not the case for the low-mass white dwarf in K4−46 and its small mass progenitor. A minor contribution to the observed Ne enhancement could come from the shallower gradient along the Galactic disc displayed by Ne compared to O, accounting for [Ne/O] = +0.2 at K4−46 galactocentric distance (Maciel & Quireza 1999). Instead, the majority of the observed Ne enrichment is probably intrinsic to the wind of the Mira that feeds the nebula. In fact, as discussed by Marigo et al. (2003) in the contest of stellar evolution, planetary nebulae with high He overabundance show Ne to be enhanced by a factor of 5/6 with respect to O.

REFERENCES

Allen D. A., 1974, MNRAS, 168, 1

Allen D. A., 1983, MNRAS, 204, 113

Allen D. A., 1984, Publ. Astron. Soc. Australia, 5, 369

Arenou F., Grenon M., Gomez A., 1992, A&A, 258, 104

Asplund M., Grevesse N., Sauval A. J., 2005, in Barnes T. G., Bash F. N., eds, ASP Conf. Ser. Vol. 336, Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis. Astron. Soc. Pac., San Francisco, p. 25

Belczynski K., Mikoajewska J., Munari U., Ivison R. J., Friedjung M., 2000, A&AS, 146, 407

Binette L., Ferruit P., Steffen W., Raga A. C., 2003, Revista Mexicana Astron. Astrofisica, 39, 55

Bond H. E., 1976, PASP, 88, 192

Carraro G., Ng Y. K., Portinari L., 1998, MNRAS, 296, 1045

Chen L., Hou J. L., Wang J. J., 2003, AJ, 125, 1397

Corradi R. L. M., Livio M., Balick B., Munari U., Schwarz H. E., 2001, ApJ, 553, 211
Costa R. D. D., de Freitas-Pacheco J. A., 1994, A&A, 285, 998
de Freitas-Pacheco J. A., Costa R. D. D., 1992, A&A, 257, 619
Drimmel R., Cabrera-Lavers A., López-Corredoira M., 2003, A&A, 409, 205
Feast M. W., Whitelock P. A., Carter B. S., 1990, MNRAS, 247, 227
Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, PASP, 110, 761
Fiorucci M., Munari U., 2003, A&A, 401, 781
Friel E. D., Janes K. A., Tavarez M., Scott J., Katsanis R., Lotz J., Hong L., Miller N., 2002, AJ, 124, 2693
Gerhz R. D., Truran J. W., Williams R. E., Starrfield S., 1998, PASP, 110, 3
Gil-Pons P., Garcia-Berro E., Jose J., Hernanz M., Truran J. W., 2003, A&A, 407, 1021
Götz W., Huth H., Hoffmeister C., 1957, Veröffentlichungen Sternw. Sonneberg, 4, 123
Henden A., Munari U., 2001, A&A, 372, 145
Hernanz M., 2005, in Hameury J. M., Lasota J. P., eds, in ASP Conf. Ser. Vol. 330, The Astrophysics of Cataclysmic Variables and Related Objects. Astron. Soc. Pac., San Francisco, p. 265
Hetzler C., 1936, ApJ, 83, 372
Hoffmeister C., Richter G., Wenzel W., 1985, Variable Stars. Springer-Verlag, Berlin
Johnson H. L., 1966, ARA&A, 4, 193
Kenyon S. J., 1986, The Symbiotic Stars. Cambridge Univ. Press, Cambridge
Kohoutek L., 1965, Bull. Astron. Inst. Czechoslovakia, 16, 221
Kohoutek L., 1978, in Terzian Y., ed., Proc. IAU Symp. 76, Planetary Nebulae. Reidel, Dordrecht, p. 47
Kondratyeva L. N., 1992, SvA, 36, 624 (K92)
Kondratyeva L. N., Denissyuk E. K., 2008, A&A, 479, 529 (KD08)
Lee T. A., 1970, ApJ, 162, 217
Luck R. E., Gieren W. P., Andrievsky S. M., Kovtyukh V. V., Fouque P., Pont F., Kienzle F., 2003, A&A, 401, 939
Luna G. J. M., Costa R. D. D., 2005, A&A, 435, 1087
Maciel W. J., Quireza C., 1999, A&A, 345, 629
Marigo P., Bernard-Salas J., Pottasch S. R., Tielens A. G. G. M., Wesselius P. R., 2003, A&A, 409, 619
Munari U., 1997, in Mikolajewska J., ed., Physical Processes in Symbiotic Binaries and Related Systems. Copernicus Foundation for Polish Astronomy, Warsaw, p. 37
Munari U., Zwitter T., 2002, A&A, 383, 188
Neckel Th., Klare G., 1980, A&AS, 42, 251
Nussbaumer H., Schild H., Schmid H. M., Vogel M., 1988, A&A, 198, 179
Pedicelli S. et al., 2009, A&A, 504, 81
Perek L., Kohoutek L., 1967, Catalogue of Galactic Planetary Nebular. Academia Publishing House of the Czechoslovak Academy of Sciences, Prague
Pettit E., Nicholson S. B., 1933, ApJ, 78, 320
Phillips J. P., 2007, MNRAS, 376, 1120
Rubin R. H., 1970, A&A, 8, 171
Sabbadin F., Falomo R., Ortolani S., 1987, A&AS, 67, 541 (S87)
Santander-Garcia M., Corradi R. L. M., Whitelock P. A., Munari U., Mampaso A., Marang F., Boffi F., Livio M., 2007, A&A, 465, 481
Schonberner D., 1989, in Torres-Peimbert S., ed., Proc. IAU Symp. 131, Planetary Nebulae. Kluwer, Dordrecht, p. 463
Sokoloski J. L., 2003, in Corradi R. L. M., Mikolajewska J., Mahoney T. J., eds, ASP Conf. Ser. Vol. 303, Symbiotic Stars Probing Stellar Evolution. Astron. Soc. Pac., San Francisco, p. 202
Tammann G. A., Sandage A., Yahil A., 1979, Les Houches Summer School Lectures Notes. University of Basel, Basel, Switzerland
Whitelock P. A., 1987, PASP, 99, 573
Whitelock P. A., 2003, in Corradi R. L. M., Mikolajewska J., Mahoney T. J., eds, ASP Conf. Ser. Vol. 303, Symbiotic Stars Probing Stellar Evolution. Astron. Soc. Pac., San Francisco, p. 41
Whitelock P. A., Feast M. W., Roberts G., Carter B. S., Catchpole R. M., 1983, MNRAS, 205, 1207
Whitelock P., Feast M., Catchpole R., 1991, MNRAS, 248, 276
Whitelock P. A., Feast M. W., Marang F., Groenewegen M. A. T., 2006, MNRAS, 369, 751
Whitelock P. A., Feast M. W., van Leeuwen F., 2008, MNRAS, 386, 313

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Our BVR_CI_C photometry of K4−46.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TEX/LATEX file prepared by the author.