Shock fronts in the symbiotic system BI Crucis

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ABSTRACT

We investigate the symbiotic star BI Crucis (BI Cru) through a comprehensive and self-consistent analysis of the spectra emitted in three different epochs: 1960s, 1970s and late 1980s. In particular, we would like to find out the physical conditions in the shocked nebula and in the dust shells, as well as their location within the symbiotic system, by exploiting both photometric and spectroscopic data from radio to UV. We suggest a model which, on the basis of optical imaging, emission-line ratios and spectral energy distribution profile, is able to account for collision of the winds, formation of lobes and jets by accretion onto the white dwarf (WD), as well as for the interaction of the blast wave from a past, unrecorded outburst with the interstellar medium (ISM). We have found that the spectra observed throughout the years show the marks of the different processes at work within BI Cru, perhaps signatures of a post-outburst evolution. We then call for new infrared and millimeter observations, potentially able to resolve the inner structure of the symbiotic nebula.

Key words: binaries: symbiotic – stars: individual: BI Cru.

1 INTRODUCTION

BI Crucis (BI Cru) is a dusty (D-type) symbiotic system (SS) (Kenyon, Fernandez-Castro & Stencel 1986) which hosts an early Mira whose pulsation period is 280 d (Whitelock et al. 1983), and a hot star of $T_\ast \sim 26500$ K (Rossi et al. 1988, hereafter R88). With respect to other dusty SSs, BI Cru shows a less strong IR excess which can be attributed to thermal emission of relatively cool dust (Angeloni et al. 2007a).

The discovery of an associated bipolar nebula with a total extent of 1.3 pc (Fig. 1) by Schwarz & Corradi (1992, hereafter SC92) pointed out a strong morphological similarity between BI Cru and He2-104, the Southern Crab. However, the BI Cru nebula seems to have a dynamical age of 3000 yr, being thus at a slightly different evolutionary age with respect to the He2-104 one (Corradi & Schwarz 1993, hereafter CS93).

Previous studies by Morris (1987) proposed a binary model for the formation of bipolar planetary nebulae via variable accretion rates onto the WD. Jets and fast winds would be thus naturally created, but for a meaningful modelling of BI Cru at least two other elements should be taken into account, namely, the bipolar nebula expands at as high velocities as the jets (200 km s$^{-1}$, CS93), and there are hints of multiple events, such as periodic (every ~1000 yr, CS93) hydrogen shell flashes that may have occurred on the WD surface.

Bipolar jets and lobes suggest the presence of an accretion disc, whose formation may be plausible assuming a typical accretion rate of $10^{-7}$ M$\odot$ yr$^{-1}$ (Morris 1987). CS93 suggest that the fast winds from the hot star are produced by thermonuclear runaways on the surface of the WD. Disc instabilities are less indicated because stable hydrogen burning occurs only in a very little range of accretion rates, which would constrain the binary parameters.

Previous modelling of SSs in different phases of outburst and quiescence (Contini, Angeloni & Rafanelli 2009b; Angeloni et al. 2007a, and references therein) led to recognize some main dynamical mechanisms that can be summarized by: the collision of the stellar winds which leads to shocked nebulae at different location on the orbital plane, the formation of a disc as a consequence of accretion phenomena, the ejection of jets and lobes perpendicular to the orbital plane, and the outburst of the WD at the origin of the blast wave propagation outwards in the interstellar medium (ISM). Furthermore, also the dust shells emitted by the Mira contribute to the line and continuum spectra and might be responsible for obscuration episodes.

In this paper, we investigate the origin of the emission fluxes at different epochs, analysing the spectral and morphological appearance of BI Cru. On the basis of the observational and theoretical evidences described previously, we will account for episodes of wind collisions, ejection of lobes and jets due to the accretion processes, and expansion of the blast wave in the surrounding medium as a consequence of past outbursts of the WD.

Quantitative information can be derived only by modelling the 1962 spectrum presented by Henize & Carlson (1980, hereafter HC80), which provides intensities and velocities of several...
observed lines. Further, important information can be obtained by the observation of the broad Hα line reported by Whitelock et al. (1983) and by the polarization of its wings discussed by Harries (1996). Eventually, some upper and/or lower limits to the physical parameters derived from the spatial distribution of some important emission lines (e.g. [O ii], [O iii]) were found by SC92.

We adopt the models presented for He2-104 and for R Aqr by Contini & Formiggini (2001, 2003, respectively). There, the winds from the WD and the red giant star collide head-on between the stars and head-on-back outwards the binary system, leading to a network of shock fronts in the equatorial plane of the binary system (Girard & Willson 1987). Moreover, the jets from the accretion disc, colliding with the circumstellar matter, give origin to the bipolar nebula in the perpendicular direction (Contini & Formiggini 2003). In fact, the jet velocity and the velocities observed in the bipolar nebula are similar (∼200–250 km s⁻¹).

The modelling of line and continuum spectra makes use of SUMA, a code that simulates the physical conditions of an emitting gaseous nebula under the coupled effect of photoionization from an external source and shocks. The important role of dust is investigated following Angeloni et al. (2007a,b,c).

The observations of BI Cru at different epochs are presented in Section 2. The 1962 spectra are analysed in Section 3, the broad Hα line is extensively discussed in Section 4 and the bipolar lobes are modelled in Section 5. The continuum spectral energy distribution (SED), calculated consistently with the line spectra, is compared with the data in Section 6. Discussion and concluding remarks follow in Section 7.

1 http://wise-obs.tau.ac.il/~marcel/suma/index.htm

2 OBSERVATIONAL DATA

SSs are rarely observed with a clear long-term strategy through the years. For most objects, the data from the literature are either the result of specific observations or belong to large surveys of those generally said ‘peculiar emission-line stars’ such as PNe, Novae, CVs, etc. Unfortunately, this is also the case of BI Cru, since its discovery on Michigan-Mount Wilson Southern Hα Survey plates in 1949. In the following, we summarize the data we have exploited in order to constrain our physical interpretation of this SS.

2.1 Photometric data

Besides the two upper limits (namely, missed detections) reported in Purton et al. (1982), the only information we have about the radio-mm wavelength range in BI Cru comes from the survey by Ivison et al. (1995, Fig. 2, bottom panel). Unfortunately, this implies that there is no way to investigate any radio variability, which may be expected according to its specific nature of SS.

With regards to the IR photometric data, it is worth mentioning that there is a reasonable agreement between observations taken at different times (Fig. 2, top panel). This means that our discussion of the continuum SED is not invalidated by the well-known IR variability mainly ascribed to the Mira pulsations. The data come from the IRAS Point Source Catalog (the 60-μm point being actually an upper limit) and the Midcourse Space Experiment Point Source Catalog (Version 2.3, Egan, Price & Kraemer 2003) for the longer wavelengths, and from Munari et al. (1992) and the Two Micron All Sky Survey (2MASS) survey for the NIR range.

2.2 Spectroscopic data

The absence of a long-term strategy in observing BI Cru has not prevented to recognize an intrinsic variability of both emission and absorption lines since the late 1940s. In particular, variations in
Hz intensity were suspected already by HC80, which pointed out that the line was stronger in 1950–1951 than in 1949. Moreover, they reported on a Mount Stromlo slit spectogram obtained in 1962 which shows an emission-line spectrum of relatively high excitation, superposed on a weak bluish continuum (HC80, Table 1).

In the 1970s, Lee (1973) noted on a spectrum taken in 1968 the presence of strong unusual emission features, probably due to Fe II, as well as a very strong Hα and a moderately strong Hγ. Allen (1974), on the other hand, recorded more than 40 lines of Fe II, in addition to Balmer emission lines. Interestingly, he found rather broad emission lines and a weak violet component to Hγ displaced from the principal line by several hundred km s$^{-1}$.

In any case, the most remarkable difference between the 1962 and 1974 spectra is the presence of [O ii], [Ne ii] and [S ii] with different FWHM in 1962, and their absence in 1974 (HC80).

In the 1980s, Whitelock et al. (1983) presented some infrared (IR) photometry, from which they deduced the evidence of a possible secular decrease in intensity between 1979 and 1982, as well as new optical spectra taken in 1974 just 55 d before the Allen’s spectrum. In these spectra, surprisingly, a strong Hz emission was evident showing blue displaced P Cyg absorption and extensive emission wings with FWHM of $\sim1500$–$2000$ km s$^{-1}$, and Fe II lines with a P Cyg profile where the $E - A$ radial velocity difference was of 145 km s$^{-1}$.

A few years later, R88 analysed a spectrum taken in 1983 with the 1.5-m ESO telescope at La Silla. Strong Hz emission and prominent He I lines confirmed that BI Cru was in a fairly high-ionization stage. Several Fe II emission lines were also present (Fig. 3). The spectrum observed by R88 shows strong Hz and blend of Fe II. R88 calculated a minimum blackbody (bb) $T = 26,500$ K for the hot star and referred to two emission components in Hz of 110 and 350 km s$^{-1}$, with a violet shifted absorption extending from 0 to $-300$ km s$^{-1}$.

In the 1990s, SC92 finally reported the discovery of a bipolar nebula associated with BI Cru (Fig. 1), whose morphology and derived expansion velocity (420 km s$^{-1}$) immediately suggested an evolution similarity with He2-104, the ‘Southern Crab’. The 1986 low-resolution and 1988 high-resolution spectra presented there and in the following papers (such as in CS93) pointed out significant optical-UV spectral changes between 1986 and 1987, on a time-scale $\leq$ 1 yr. Since then, the link between SSs and bipolar planetary nebulae has become stronger, demonstrating the need of improved models to explain such complex sets of data.

### 3 THE 1962 SPECTRUM

We start by analysing the spectrum presented by HC80 and taken on 1962 June 14. We focus mainly on the BI Cru emission lines in 1962, because there are too few forbidden lines in the 1983 spectrum reported by R88 to allow a reliable modelling of the nebulae.

#### Table 1. Optical line ratios to Hβ and model parameters.

| Line           | Velocity | Obs$^a$ | m1    | m2    | m3    | m4    | $m_{av}$ |
|----------------|----------|---------|-------|-------|-------|-------|----------|
| [Ne III]λ3869+3969 | −152     | 0.17    | 0.26  | 0.004 | 0.154 | 0.06  | 0.113    |
| [S II]λ4068+4077   | −174     | 0.03    | 0.001 | 0.0   | 0.3   | 0.008 | 0.02     |
| [O III]λ4363       | −189     | 0.09    | 0.11  | 0.001 | 0.15  | 0.09  | 0.06     |
| He II λ4471        | −79      | 0.17    | 0.048 | 0.11  | 0.89  | 0.05  | 0.13     |
| He II λ4686        | −227     | 0.13    | 0.0016| 0.2   | 5.e-4 | 0.005 | 0.11     |
| [O III]λ5007+4959   | −480     | 0.33    | 0.6   | 0.043 | 1.6   | 0.44  | 0.35     |

$^a$Reddening corrected (from HC80).

$^b$In [erg cm$^{-2}$ s$^{-1}$].

$^c$RDo: radiation dominated model with radiation flux and shock acting on opposite edges of the nebula; RD: radiation dominated model with radiation flux and shock acting on the same edge; SD: shock dominated model ($U = 0$). See text for details.

$^d$From HC80.

$^e$Evaluated from the observed [O II]5007+4959/[O III]4363 (Column 3).
In 1962, the complex and unusual spectrum includes He II 4686 and blended N III 4634, 41, 42, while [O III] is not visible. He I 4043 and 4026 show absorptions and P Cyg profiles. These lines led HC80 to suggest that one component of the system possesses an expanding atmosphere with an improbably large velocity of 1940 km s\(^{-1}\), and to conclude that the forbidden lines may arise in a region apart from the one in which the permitted lines occur.

The analysis of the ion velocities shows three distinct velocity regimes: one at \(-55\) km s\(^{-1}\) represented only by H I, a second at \(-115\) km s\(^{-1}\) which includes He I and Fe II and a third at about \(-180\) km s\(^{-1}\) which includes He II and the forbidden lines. The individual velocities give an approximate mean error of \(\pm 20\) km s\(^{-1}\). Only the [O III] 4959 line shows a velocity of \(\sim 377\) km s\(^{-1}\). In Table 1, the observed intensities corrected for reddening and the FWHM are shown for the forbidden lines and He permitted lines.

Since the several emitting components recognizable in a symbiotic spectrum can be alternately visible or hidden from view depending on the different configuration with respect to the line of sight, as well as on the activity phase of the system, in the following we start identifying the emitting nebulae through their emission signatures. Then, we try to interpret the spectra on the basis of the orbital motion and of the activity status of BI Cru.

### 3.1 The colliding-wind scenario

In the last years, several observational evidences have proved that compact hot stars loose mass through fast (1000 km s\(^{-1}\)), low-density wind. Regarding SSs, Nussbaumer, Schmutz & Vogel (1995) were the first that, by analysing observations of a fast wind from the compact object, called for a symbiotic colliding-wind scenario.

The winds from the hot and the cool stars collide within and outside the system, hence creating a complex network of wakes and shock fronts that result in a complicated structure of gas and dust nebulae (Nussbaumer 2000). In the light of this scenario, one can consider that two main shock fronts develop from the head-on collision of the winds between the stars. The binary colliding-wind configuration discussed in some theoretical works, e.g. Girard & Willson (1987) and Kenny & Taylor (2005), describes one strong shock front facing the WD and the other, very weak, facing the cool giant. Similarly, in the extended circumbinary region, two shock fronts develop from the head-on-back collision of the winds: one expanding outwards and the second, virtually negligible, facing the system centre. This latter shock network corresponds to the concentric colliding-wind configuration of e.g. Kwok (1988), which is a theoretical basis to the more realistic picture of shock fronts disrupted by instabilities.

Generally, we can figure out that for all shock waves there is an upstream region, where the gas enters into the shock front, and a downstream region, on the opposite side. The shock front discontinuity is very thin, the thinner the faster the shock velocity.

The gas entering the strong shock front is thermalized and a high-temperature region appears immediately behind the discontinuity, in the downstream region. On the opposite side of the shock front, upstream, the temperature of the gas is slightly increased by precursor radiation from the hot slabs of the gas downstream and by radiation from the WD, without reaching temperatures as high as those in the immediate post-shock region, though. The gas recombines following a high cooling rate due to the high pre-shock densities and to compression downstream.

The key parameter is obviously the shock velocity, \(V_s\). For high-velocity shocks, the very high temperature reached in the post-shock region leads to the X-ray emission observed in several SSs. Moreover, broad strong lines can also be observed along the whole electromagnetic spectrum, particularly the coronal lines in the IR (e.g. Angeloni et al. 2007a): therefore, from the spectral point of view, different line profiles trace different velocity regimes, allowing to highlight the different physical conditions within a SS.

Also BI Cru shows the signatures of the colliding-winds, because the range of velocities observed in literature (Section 2.2) fits with both the head-on shock between the stars (‘high-velocity’ regime) and the expanding shock front onwards the system (‘low-velocity’ regime), and cannot be reconciled with a single velocity model. For instance, the [O III] 4959 line observed in the central system corresponds to \(\sim 400\) km s\(^{-1}\), while [N II] lines observed in the lobes display widths of \(\sim 200\) km s\(^{-1}\). Lower velocities (\(\sim 50\) km s\(^{-1}\)) of optical-UV lines appear also in the 1962 spectra reported in HC80.

In the frame of colliding winds already exploited to interpret many others symbiotic spectra (Contini, Angeloni & Rafanelli 2009a, and references therein), we schematically refer to the nebula downstream of the main shock fronts: (i) the head-on shock between the stars facing the hot star (named hereafter reverse shock) and (ii) the head-on-back shock propagating outwards the system (hereafter expanding shock). Moreover, we also consider (iii) the shock front accompanying the expansion of the lobes (Section 5). The nebula downstream of the reverse shock between the stars is thus characterized by photoionizing radiation and shocks acting on the same edges of the shocked nebula, while the models describing the expanding shock propagation outside the system are characterized by photoionization and shocks acting on opposite edges. For both the inverse and expanding shocks, the shock velocity is suggested by the FWHM of the line profiles, while the other physical conditions in the emitting region downstream are constrained by the observed line ratios.

The models must then account consistently for shocks and photoionization. This is one reason why the SUMA code is particularly suited for this kind of spectral analysis applied to SSs. The input parameters of the code are those relative to the shock: the pre-shock density \(n_0\), the shock velocity \(V_s\), the pre-shock magnetic field \(B_0\) and those relative to photoionization: the hot star ionizing radiation flux, its colour temperature \(T_e\), and the ionization parameter \(U\). The chemical abundances of He, C, N, O, Ne, Mg, Si, S, Ar and Fe, relative to H, the dust-to-gas ratio \(d/g\) and the geometrical thickness of the nebulae \(D\) are also accounted for. Note that \(D\) is a lower limit in radiation-bound models. Dust reprocessed radiation and bremsstrahlung are consistently calculated throughout the nebulae, as well as the dust grain sputtering.

Specifically, the line and continuum fluxes downstream are calculated integrating throughout many plane-parallel slabs (up to 300) with different geometrical widths derived automatically from the temperature gradient. By the way, the plane-parallel geometry is necessary in the interbinary region where the collision of the winds is head-on. It is also valid in the circumbinary region where the radius of the expanding shock created by the head-on-back interaction of the outflowing winds from the stars is large enough.

Furthermore, since the matter is highly inhomogeneous at the shock fronts because of instabilities at the nebula interface [e.g. the Rayleigh-Taylor (R-T), Kelvin-Helmholtz (K-H), Meshkov-Richtmyer (M-R) instabilities], different physical conditions should be accounted for, particularly regarding the density.
3.2 Modelling the line spectrum

The modelling of a line spectrum is based on some basic points. The most significant are the following.

(i) Recombination lines (e.g. Hβ, He i, He ii) depend strongly on the temperature of the star and on the ionization parameter.
(ii) Line ratios of a single element from the same ionization level but corresponding to a different quantum configuration depend on the physical conditions of the emitting gas (density, temperature, etc).
(iii) Line ratios of single elements from different ionization stages depend on the ionization rates: radiative and/or collisional. The radiative ones are strong at temperatures \( \lesssim 10^4 \) K, while the collisional ones are high at high temperatures. Therefore, collisional ionization rates are important when shocks are at work.
(iv) Ratios of lines from different elements are strongly linked to the relative abundances.

For a spectrum with a rich number of lines, these rules act together and constrain the models. Generally, in SSs, the spectra from different nebulae must be accounted for at the same time. The results will depend on the relative weights adopted to sum up single nebula spectra.

The spectrum from BI Cru in 1962 shows the He i and He ii line ratios to Hβ which are examples of condition (i) and the \([\text{O}
\text{ii}]/\text{Hβ}\) ratio which refer to condition (ii); however, lines from different levels refer to different elements leading to an uncertain modelling. Moreover, each line is characterized by a different FWHM, indicating that a pluri-nebula model must be adopted.

We have tried to complete the insufficient information derived from the line ratios from the modelling of other SSs. For instance, the model with \( V_s = 400 \text{ km s}^{-1} \) is accompanied by a high pre-shock density (\( \sim 10^6 \text{ cm}^{-3} \)) because of being located between the stars. R88 indicated a WD temperature of at least \( \sim 26\,500 \) K, Bohigas et al. (1989) proposed a pre-shock magnetic field of \( \sim 10^{-3} \text{ G} \) in SSs similar to that of isolated giants. This value was confirmed, for example, in the CH Cyg system by Crocker et al. (2001) and Contini et al. (2009b). The nebula network throughout SSs is further complicated because each of the nebulae is characterized by relative abundances differing from those of the WD atmosphere or those of the red giant (Contini 1997). We discuss the abundances in the following: in our first trial, we have used solar abundances (Allen 1973).

3.3 The selected models

We have run a grid of models covering reasonable ranges of all the input parameters in order to find the best and most consistent fit of calculated to observed line ratios.

Four models are selected amongst the best fitting ones and are described in the bottom of Table 1. For each of them, \( T_s = 26\,500 \) K and a dust to gas ratio \( \rho / \rho_d = 4 \times 10^{-4} \) by mass are adopted.

Models labelled with RD indicate a radiation-dominated case, radiation flux and shock act on opposite edges of the nebula (expanding shock). Models labelled with RD indicate a radiation-dominated case, radiation flux and shock act on the same edge (reverse shock); models labelled with SD are shock dominated (ionization parameter \( U = 0 \)).

and calculated absolute Hβ fluxes \((I_{\text{Hβ}})\) are given in Table 1.

The absolute fluxes of the lines are very different for different models, depending particularly on \( n_0 \). Mathematically, the weights \( w_i \) roughly compensate for the line fluxes. Physically, they represent the \( \eta \) factors which are introduced in Section 6 in order to compare fluxes calculated at the nebula with fluxes observed at Earth.

The results obtained by modelling the line spectrum lead to a better understanding of BI Cru system. For instance, the contribution of model m2, which is characterized by \( V_s = 150 \text{ km s}^{-1} \) and \( n_0 \sim 10^6 \text{ cm}^{-3} \), leads to a better fit of the He i/He ii line ratio. This shock velocity is also suitable to the expanding shock, even if models m1 and m2 show different pre-shock densities by a factor of \( \sim 100 \), and a different ionization parameter. This confirms that the expanding shock is very disrupted and propagates in the a non-homogeneous medium.

show narrow profiles. In the frame of the colliding-wind picture, model m4 represents the reverse shock front between the stars which explain the \textit{Infrared Space Observatory} (ISO) IR spectra of D-type SSs, so we adopt \( n_0 = 10^3 \text{ cm}^{-3} \) (Angeloni et al. 2007a). Model m4 is radiation dominated and represents the shocked nebula downstream of the shock front facing the hot star.

The \([\text{O}
\text{ii}]\) FWHM (200 km s\(^{-1}\)) indicates that a model with \( V_s = 200 \text{ km s}^{-1} \) should be adopted (model m1). To further constrain this model, we note that such velocities are characteristic of the expanding shock. We adopt therefore pre-shock densities of \( \sim 10^5 \text{ cm}^{-3} \) as, for example, for CH Cyg (Contini et al. 2009a).

Model m3 shows a very high He i \( 4471/\text{Hβ} \) ratio and a low \( V_s \), in agreement with the FWHM reported by HC80. Lower velocities (\( \sim 50–70 \text{ km s}^{-1} \)) are suitable to the expanding shock front at a large distance from the stars, therefore, model m3 is characterized by \( U = 0 \). Model m3 represents the shock dominated case, i.e. the ionization conditions throughout the nebula are dictated only by the shock, the flux being absorbed by some intervening matter (a dust shell?).

The geometrical thickness \( D \) is constrained by the dimensions of the system, while the other parameters (e.g. \( U \)) are chosen phenomenologically for all the models. Models m1, m3 and m4, which are dictated by the observations, either refer to a rather strong shock or are shock dominated, leading to He i/He ii \( \lesssim 10 \). The observations show He i/He ii \( \sim 1 \), suggesting that another nebula dominated by a strong photoionizing flux, should contribute to the averaged spectrum. Model m2 with \( U = 25 \) produces a very high He ii/Heβ line ratio.

The models are summed up adopting relative weights \( w_i \) which lead to the fit of all the observed line ratios at least within a factor of 2 (model \( m_{\text{avg}}, \) Table 1) with a larger precision for the strongest lines.

Complex models such as the pluri-nebula ones used for BI Cru, require the combination of two calculation processes. The first is achieved by the \texttt{SUMA} code which calculates the spectrum emitted from a single nebula, the second is an ad hoc programme which provides the weighted sum of the single-nebula spectra. The results of the two processes are cross-checked until a fine tune between the observed and calculated line ratios is obtained. The whole procedure requires a large grid of models which are constrained by the data, by the range of the physical parameters in SSs, and by consistency of line and continuum modelling.

The average line ratios are calculated by

\[
(I_i/I_{\text{Hβ}})_{\text{av}} = \sum_i (I_i/I_{\text{Hβ}})(I_{\text{Hβ}})w_i/\sum_i (I_{\text{Hβ}})w_i,
\]

where \( i = 1 \) to 4 refers to the models. The calculated line ratios \((I_i/I_{\text{Hβ}})\) and calculated absolute Hβ fluxes \((I_{\text{Hβ}})\) are given in Table 1.

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Shock velocities through clouds of different densities are inversely proportional to the density square root ratio: this is evident when comparing $V_s$ and $n_0$ of models m2 and m3. In turn, model m3 shows both lower $V_s$ and $n_0$ than model m1, thereby indicating that the corresponding nebula has reached a larger distance from the central system than that corresponding to the model m1.

A sketch showing the location of the shock fronts within BI Cru SS is shown in Fig. 4.

Note that calculated [Ne III]/Hβ and [S II]/Hβ can be ameliorated adopting relative abundances of Ne and S slightly higher than solar by a factor of $\sim$1.5. We can deduce directly from the fitting results the abundances of Ne and S because they are not strong coolants. Ne/H and S/H higher than solar might be characteristic of WD atmospheres, although in BI Cru they are highly diluted by merging with the ISM.

The electron density $N_e$ and the electron temperature $T_e$ measured from the observations appear in the bottom of Table 1 for comparison.

Using SUMA, the spectra emitted from each nebula result from integration throughout different gas regions downstream characterized by different physical conditions which derive from the cooling rate, from radiation transfer of the primary and secondary (diffuse) radiation flux, and from compression which characterizes models accounting for the shocks. We present in Fig. 5 the profiles of the electron density $N_e$, electron temperature $T_e$, and of the fractional abundance of the most significant ions which lead to different lines ratios. The lines in Table 1 correspond to low and intermediate ionization levels, meaning that most of the lines are emitted from gas at $\lesssim$$5 \times 10^4$ K.

3.4 The Fe II lines

Finally, we refer to the several permitted Fe II lines, often recorded in BI Cru spectra (Fig. 3) but not included in Table 1, which deserve a special discussion. Emission lines of Fe II are seen in the ultraviolet spectra of many SSs (e.g. RR Tel, AG Peg). In some objects, optical multiplets of Fe II are also seen in emission, indicating that the ultraviolet resonance lines are optically thick (Penston 1987).

Transitions between even 5-eV levels and even 3-eV levels correspond to the permitted optical multiplets 27, 28 and 29, which are all observed in BI Cru, while forbidden [Fe II] lines are rarely observed. Therefore, an overabundance of iron cannot help to explain the Fe II emission by a photoionization model, but the Fe II region should be heated by an additional mechanism; that is, the Fe II spectrum is not produced directly by photoionization but more probably by shocks. Indeed, it is generally believed that collisional excitation is responsible for the bulk of the Fe II emission, and it has been shown how these lines may represent, especially in SSs, one of the most direct traces of fast outflows of WD winds (Eriksson, Veenhuizen & Nilsson 2007). Inelastic collisions with electrons excite the odd parity levels near 5 eV which then decay into the optical and UV lines. Self-fluorescence and fluorescent excitation by Lyα are also important sources of excitation (Sigut & Pradhan 2003).

Verner et al. (2000) have shown that at low densities ($n_e \lesssim 10^2$–$10^4$ cm$^{-3}$), the permitted optical Fe II lines are relatively weak, the reason being that the 63 lowest levels, the most populated at these densities, are all of the same (even) parity and are able to radiate only forbidden lines. The situation dramatically changes near $10^6$ cm$^{-3}$ because, then, levels of odd parity are populated by collisions, enough to produce the permitted lines. Therefore, if both the permitted Fe II and forbidden lines were produced in the same region, the density should be larger than $10^6$ cm$^{-3}$ and lower than $10^{8}$ cm$^{-3}$ because forbidden lines would be collisionally de-excited (Véron-Cetty, Joly & Véron 2004).

In the case of BI Cru, it is interesting to note that models m1 and m4 correspond to $2 \times 10^5$ cm$^{-3}$ and $10^6$ cm$^{-3}$, respectively, which lead to $n_e > 10^6$ cm$^{-3}$ downstream. In this density range, the Fe II lines can then be produced without invoking a different emission region for permitted and forbidden lines, conversely to what stated by HC80.

4 THE BROAD Hα LINE

Whitelock et al. (1983) reported on a strong Hα with blue displaced P Cyg absorption at $-228$ km s$^{-1}$ and extensive emission wings with FWHM of $\sim$1500–2000 km s$^{-1}$, observed in the 1974 spectra. On 1984 February, R88 observed the Hα region, noting a double emission with a strong and broad violet-shifted absorption extending to about $-300$ km s$^{-1}$. The Hα absorbed portion was thought to arise from gas in front of an H II region with a large velocity gradient, hence suggesting a possible location in the cool giant wind accelerated by the intense radiation of the hot component. SC92 recorded, on a high-resolution spectrum taken in 1988, an Hα line with a full width at zero intensity (FWZI) of more than 3000 km s$^{-1}$ (Fig. 6): such velocities are generally explained by scattering in an accretion disc (Robinson et al. 1989).

Linear spectropolarimetry of BI Cru was presented by Harries (1996). Interestingly, he found that the broad blue Hα wing is unpolarized, while the red one is strongly polarized. As already suggested by R88, Harries (1996) proposed that the Hα emission is produced in two separate velocity regimes: the central narrow peak being formed in the slow moving part of the cool component wind, while the broad component in the part of the wind approaching the hot source. The spectropolarimetric observations supported this hypothesis, although Harries (1996) believed the source of the high-velocity material had to be identified in a bipolar flow.
The broad blue wing of Hα could neither be emitted from the accretion disc because the blue wing and the red wing show different polarization. Actually, lines emitted from an accretion disc are generally double peaked with asymmetry in peak heights. The modelling by Robinson et al. (1994) leads to two peaks with similar intensity, while in SSs that are believed to contain an accretion disc, eclipses are invoked to explain unequal emission peaks. For instance, an exceptionally broad nuclear Hα was observed in M2–9 by Balick (1989) and explained as emitted from the accretion disc because double-peaked. However, the ratio of the red and blue component intensities and a line width of 11 000 km s⁻¹ deserve a different interpretation.

Our analysis of the exceptionally broad Hα in BI Cru focuses on the evidence that the blue wing is unpolarized, meaning that this part of the line is formed out of the scattering region, and excluding therefore broadening by scattering by a high opacity (Mikolajewska, Selvelli & Hack 1988).

Moreover, in Fig. 3, the Hα line appears abnormally broad, whereas the other strong permitted lines (e.g. He I 5876 and 6676), which should be emitted from the same emitting gas region, are both much narrower.

According to our recent interpretation concerning the appearance of a broad Lyα in the CH Cyg spectra at the end of the active phase 1977–1986 (Contini et al. 2009a), we would like to explain the broad Hα line in BI Cru by means of the theory of charge transfer reactions between ambient hydrogen atoms and post-shock protons at a strong shock front (Heng & Sunyaev 2008). Particularly, recall that in the circumstellar side of the WD opposite to the red giant, the effect of symbiosis is less enhanced. Here, we can apply to the WD outburst the theory developed by Chevalier (1982) for Type II supernovae (SNe).

We rely on the hypothesis of CS93 that multiple bursts could occur in BI Cru, similarly to He2-104. The WD temperature ∼26 500 K found by modelling the line spectra is an indication that the last burst is completely run out. Whitelock et al. (1983) reported on Fe II narrow lines and Allen’s (1984) spectrum is rich in N III and He II lines which could be emitted from the expanding region. According to the shock front network created by collision of the wind, the expanding shock front is located in the circumbinary side of the system opposite to the red giant star. Therefore, we can apply Chevalier’s theory.

Actually, Kawabata et al. (2009) published the optical spectra of Type II SN 2006gy at late state detection. A strong similarity with BI Cru Hα line profile (Fig. 6) can be noted.

The interaction of the freely expanding matter with the surrounding medium gives rise to a high-energy density region bounded by
where $E$ is the total energy (twice the kinetic energy), $\rho_0 = A R_{BW}^2$, $\rho_0 = 1.4m_Hn_0$ and $n_0$ the density of the gas upstream.

This equation is valid for times longer than a specific time, called the time of change

$$t_s = \frac{0.677M_{ej}^{3/2}}{AE^{1/2}}$$

between that of the interaction of freely expanding matter with the surrounding medium and the following one, i.e. when the flow tends towards the self-similar solution for a point explosion in a power-law density profile (Sedov 1959), $M_{ej}$ is the ejected mass.

The velocity of the blast wave is

$$V_{BW} = \frac{dR_{BW}/dt = 2/(3E/2\pi A)^{1/3}t^{-1/3}}{2}$$

On the basis that no burst has been recorded in the last 60 yr of observations, we adopt $t \sim 60$ yr as a lower limit. Following the method indicated by Contini et al. (2009a) for CH Cyg, a present blast wave velocity $V_{BW} = 1500-2000$ km s$^{-1}$, at least 60 yr after the outburst, would then translate to $V_{BW} \sim 5800-7700$ km s$^{-1}$ 1 yr after the burst. A velocity of $\sim5800$ km s$^{-1}$ is about the maximum predicted by the models of Yaron et al. (2005) for nova outbursts. A period shorter than 1 yr after BI Cru burst would lead to higher velocities. We cross-check whether 1 yr from the blast is compatible with the time of change $t_s$ (equation 2). If so, we adopt an initial velocity of 5800 km s$^{-1}$ as the escape velocity.

The results of Yaron et al. (2005) and Prialnik & Kovetz (1995) models of nova outbursts indicate that a velocity of 5800 km s$^{-1}$ is possible for a $\geq1M_\odot$ WD.

Considering an escape velocity of 5800 km s$^{-1}$ and a WD mass $M_{WD} = 1$. $M_\odot$, we obtain the radius of the WD, $R_{WD} \sim 6.7 \times 10^8$ cm. This in turn corresponds to $L_\ast \sim 7 \times 10^{35}$ erg s$^{-1}$ for $T_e = 200,000$ K, still below the Eddington luminosity. Therefore, a stellar wind could not develop from BI Cru and confirms the hypothesis of a nova-type wind.

The radius of the blast wave in BI Cru, 60 yr after the outburst, is calculated by $R_{BW} = 3/2V_{BW}t_s$, leading to $R_{BW} \sim 4 \times 10^7$ cm. The ejected mass is then calculated by equation (2). Note that $A = 1.4m_{H}n_0R_{BW}^2$ is a constant. We assume that the pre-shock density $n_0$ at a radius of $4 \times 10^7$ cm from the binary system is of the order of that of the ISM ($0.1-10$ cm$^{-3}$). Then, if $t_s = 1$ yr, $M_{ej}/n_0 = 4.8 \times 10^{-6}$ M$_\odot$ cm$^{-3}$, in agreement with Prialnik & Kovetz (1995).

We can calculate by $A$ that a density of $10^7$ cm$^{-3}$ could be found within a radius of $\leq1.2 \times 10^8$ cm from the WD.

## 5 THE BIPOLAR LOBES

The central image of BI Cru taken by SC92 (Fig. 1) is in the [N ii] light. No [O iii] and [O ii] appear in the lobes. In the 1986/1987 spectra, they have identified: H $\alpha$, He i, He ii, O i, O ii, O iii, [O iii], N ii, N iii, [S ii], Si ii, Fe ii, [Fe ii], [Fe ii], [Cl ii], [Cl iv]. The 1987 spectrum, much richer than the 1986 one, confirms the important variability of the object.

The ejecta (jets) interact with the ISM with velocities $\leq200$ km s$^{-1}$, similar to what happens in the He 2-104 ‘crab legs’. Two lobes are seen in the [N ii] light but not in the [O iii] and the [O ii], in both BI Cru and He2-104. Contini & Formiggini (2001) have modelled and discussed the formation of the ‘crab legs’ in He2-104; therefore, we follow the same modelling approach. First, we constrain the models by $[N\, ii]/[O\, ii]$ and $[N\, ii]/[O\, ii] \gg 1$. We have run a shock dominated ($U = 0$) grid of models with $V_s$ between 200 and 250 km s$^{-1}$ as measured by SC92. Fig. 7 shows that the critical line ratios result easily for $V_s = 200$ km s$^{-1}$. Higher velocities can be excluded. The pre-shock densities are $\geq10^5$ cm$^{-3}$, high
1. \( r = \) the distance of the nebula from the SS centre,
2. \( r_T = \) the radius of the nebula,
3. \( \eta = \) the distance of the nebula from the SS centre,
4. \( r_0 = 10^{-3} \) G,
5. \( r = 200 \text{ km s}^{-1} \),
6. \( r = 250 \text{ km s}^{-1} \),
7. \( r = 6584 \),
8. \( r = 3727 \),
9. \( r = 3729 \),
10. \( \eta = \) the distance to Earth (\( \sim 2 \text{ kpc} \) for BI Cru).

### 6 THE CONTINUUM SED

The observed SED of the continuum, calculated consistently with the line spectra that were extensively presented in the previous sections, is shown in Fig. 9. There are no data for the continuum flux in the years corresponding to the 1962 line spectra (Section 3).

As we have shown in previous papers (e.g. Contini et al. 2009b), a few schematic models can describe the variable spectra of SSs: therefore, we compare the combination of models calculated by the fit of the line spectrum on the basis of a data set taken on a certain time, with a mosaic of continuum data observed at very different epochs. The modelling is presented in Table 1, last row.

Model m4 (Fig. 9, left-hand panel) shows the characteristic self-absorption in the radio range already found in other SSs (e.g. H1-36, Angeloni et al. 2007b). It describes the physical conditions of the nebula downstream of the reverse shock which is characterized by relatively high densities downstream (\( > 10^{13} \text{ cm}^{-3} \)). This model shows that X-rays could be expected in 1962. Emission in the UV soft X-ray is suggested by model m2 (black lines) which explains also the data at longer wavelengths. This model represents the nebula expanding with \( V_e = 150 \text{ km s}^{-1} \). The bremsstrahlung emitted from the shock dominated model m3 (violet lines) is not directly seen throughout the SED; however, its reprocessed emission from dust may contribute to very far-IR emission (\( v < 10^{12} \text{ Hz} \)).

We suggest that the presence of many shock fronts in BI Cru should be confirmed by synchrotron radiation in the radio range, produced by the Fermi mechanism.

The line spectra are generally modelled referring to the line ratios, while the SED of the continuum is modelled on the basis of absolute fluxes. Since the observations are taken at the Earth, while the models are calculated at the nebula, we define the factor \( \eta = (ff R/d)^2 \), where \( r \) is the distance of the nebula from the SS centre, \( d \) the distance to Earth (\( \sim 2 \text{ kpc} \) for BI Cru) and \( ff \) the filling factor.

The \( \eta \) factors, depending on the distance of the nebulae from the system centre, further constrain the models.

Adopting a continuum SED similar to that observed in later epochs, we find that the radius of the different nebulae which contribute to the 1962 line spectrum are \( r_{m1} = 6.10^{13} \text{ cm} \), \( r_{m2} = 1.8 \times 10^{17} \text{ cm} \) and \( r_{m3} = 1.5 \times 10^{16} \text{ cm} \), adopting \( ff = 1 \).

The distance of the reverse shock from the hot star is \( r = 2.8 \times 10^{13} \text{ cm} \), considering that for model m4, \( U = 1 \) can be combined with \( T_e \) by means of \( F_v(r_{WD}/r^2) = U nc \), where \( F_v \) is the flux in number of photons cm\(^{-2}\) s\(^{-1}\) corresponding to \( T_e = 26 \text{ 500 K} \), and adopting \( r_{WD} = 5.4 \times 10^8 \text{ cm} \) (Section 3.3).

In Fig. 9, right-hand panel, we refer to the modelling of the lobe spectra (Section 3.3). We select a model (m5) representing the filaments in the lobes, with \( V_e = 210 \text{ km s}^{-1} \) as indicated by SC92, \( n_0 = 2 \times 10^4 \text{ cm}^{-3} \), \( B_0 = 10^{-3} \) G, \( D = 0.33 \) pc. The bremsstrahlung calculated by model m5 is then compared with the data in Fig. 9 (right-hand panel, blue lines), leading to log \( \eta = -12.5 \). SC92 indicate that the lobes had expanded to a radius \( r_1 \sim 1.3 \) pc. Combining \( \eta \) with \( r_1 \) we obtain \( ff \leq 0.001 \).

According to its nature of dusty SS, also BI Cru confirms that in order to reproduce the NIR–MIR continuum slopes, different ‘dust’ temperatures should be combined (e.g. Anandarao, Taylor...
The observed BI Cru continuum SED, from radio to UV. The data (filled circles) are described in Section 2. Thin short-dashed line (red): 250 K dust shell; short-dashed line (red): 850 K dust shell; thick short-dashed line (black): Mira component. Left-hand panel: solid lines (green): m4; long-dashed lines (blue): m1; thick solid lines (black): m2; thin solid lines (violet): m3. Both bremsstrahlung and reradiation by dust are shown for each model. Right-hand panel: solid lines (black): model m3.

& Pottasch 1988; Angeloni et al., in preparation). In BI Cru, two dust shells result from the continuum SED modelling, an internal one at a temperature of 800 K with a radius of $1.5 \times 10^{14}$ cm, and the outer one at 250 K with a radius of $1.6 \times 10^{15}$ cm, probably circumbinary.

**7 DISCUSSION AND CONCLUDING REMARKS**

We present the quantitative results obtained by the analysis of the spectra observed from BI Cru in different epochs.

1962. We analysed the spectra observed in 1962 within a colliding-wind theoretical framework (Section 3). The data of the continuum were observed many years later than those of the 1962 line spectra. Even considering a minimum set of prototypes, the emerging picture of the BI Cru nebular network is consistent.

The result obtained by modelling the line spectra indicates that in 1962 BI Cru may have been in a post-eruption ‘classical’ phase, with two main shock networks created by the collision of the stellar winds. The shock front between the stars, facing the hot star, has a velocity of $V_s = 400$ km s$^{-1}$, while the expanding shock shows different components with $V_s \approx 70$–190 km s$^{-1}$ in agreement with the observed FWHM. The shock velocities are thus similar to those found in other SSs for the reverse and expanding shocks, respectively (Angeloni et al. 2007a,b,c, and references therein).

The physical conditions (e.g. $n_e \geq 10^6$ cm$^{-3}$ downstream) which result from line modelling are responsible for self-absorption of free–free radiation in the radio range, and also indicate that both permitted and forbidden Fe II lines can be emitted from the same region.

1974. We argued that the observed broad blue wing of H$\alpha$ could not be emitted from the accretion disc because the blue wing and the red wing show different polarization. So we present in this paper a new interpretation of the H$\alpha$ broad blue wing adopting the model developed by Chevalier (1982) to explain the hydrodynamical picture in SNe after the explosion, combined with the Heng & Sunyaev (2008) theory of broad Lyman and Balmer emission-line production.

In particular, the broad blue wing of the H$\alpha$ line observed by Whitelock et al. (1983) in 1974 is explained by emission throughout the blast wave shock front created by a past ($\geq 60$ yr ago), unrecorded outburst which has now reached a radius $\leq 1$ pc. Adopting the Robinson et al. (1989) model of line formation from the accretion disc, the broad H$\alpha$ line emission should originate from the innermost regions of the disc, being always perceived only if the accretion disc is face-on, but hardly seen in other configurations. On the other hand, by Chevalier’s theory (Section 3.3) the broad H$\alpha$ line is formed within the limit of the system ($\geq 0.3$ pc) and is seen only from the side of the WD opposite to the Mira.

We have demonstrated that, even though no outbursts have been recently observed in BI Cru at least in the last 60 yr of historical observations, this does not invalidate our analysis; on the contrary, this negative evidence is exploited as a temporal constrain in the calculations.

Interestingly, the blast wave velocity ($\sim 5800$–$7700$ km s$^{-1}$) estimated for BI Cru at very early times after the outburst (Section 4) is about twice the velocity of the nova ejecta in RS Ophiuci immediately after the 1985 outburst ($\sim 2700$–$3900$, Shore et al. 1996) and after the 2006 outburst ($\sim 3300$ km s$^{-1}$, Walder et al. 2008). However, in the broad-line phase of RS Ophiuci observed 6 d after the brightness peak, the O I 1300 and [N ii] 1750 lines showed FWHM of 7000 km s$^{-1}$ (Shore et al. 1996). Moreover, the detection of X-rays from RS Ophiuci (e.g. O’Brien, Bode & Kahn 1992) was explained by shocks. X-ray emission could be expected also from BI Cru (Fig. 9).

Concluding the spectrum observed from BI Cru in 1962 indicates that we were seeing the internal region between the stars. The broad H$\alpha$ reported in 1980s and 1990s indicated that we were seeing the system from the side of the WD opposite to the Mira. We wonder whether these insights are sufficient to suggest a likely orbital period for BI Cru of $\leq 100$ yr.

1992. The lobes observed by SC92 in 1992, expanding out to 1.3 pc, are dominated by the [N ii] 6584 line. We have modelled the filaments in the lobes by constraining the model by the absence of [O iii] 3727 and [O iii] 5007. The fit of the calculated model to the observed continuum SED leads to a filling factor in the lobes of about 0.001.

Finally, in Table 2, we compare the results obtained for BI Cru with those obtained for He2-104, R Aqr and CH Cyg, all objects showing lobes and jets extending outwards.

The temperatures of the hot star are within the range of moderately WD at quiescence ($\leq 30000$ K – BI Cru) and those ($\geq 100000$ K – BI Cru).
Table 2. Comparison of BI Cru, He2-104, R Aqr and CH Cyg. Rev. and exp. stand for reverse and expanding shock, respectively.

| T_*(K) | BI Cru | He2-104 | R Aqr | CH Cyg |
|--------|--------|---------|-------|--------|
|        | Rev. | Exp. | Rev. | Exp. | Rev. | Exp. | Rev. | Exp. |
| 26000  | 26   | 50    | 130  | 80   | 150  | 35   | 80   | 35   |

дельные изменения физических условий в расширяющихся фрагментах. Один из этих шоков в системе BI Cru мог бы вести к значительному расстоянию между звездами, но геометрическая толщина облака вниз по потоку противодействует. Области, даже если линии показывают большое FWHM. В противоположность, сильно возбужденные шоки являются слабыми, а сильные шоки не могут быть отдельными в R Aqr, если даже линии показывают большое FWHM. В противоположность, сильные шоки присутствуют в BI Cru (V_s = 400 km s^{-1}), и это может быть очень сильным (V_s \leq 1500 km s^{-1}) в CH Cyg.

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