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Resolving the radio nebula around β Lyrae

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Abstract. In this paper we present high spatial resolution radio images of the puzzling binary system β Lyrae obtained with MERLIN at 5 GHz. We find a nebula surrounding the binary with a brightness temperature of $(11\,000 \pm 700)$ K approximately 40 AU across. This definitively confirms the thermal origin of the radio emission, which is consistent with emission from the wind of the B6-8 II component (mass loss of order of $10^{-7}\ M_{\odot}\mathrm{yr}^{-1}$), ionized by the radiation field of the hotter companion. This nebula, surrounding the binary, is the proof that β Lyrae evolved in a non-conservative way, i. e. not all the mass lost by the primary is accretted by the secondary, and present measurements indicate that almost 0.015 $M_{\odot}$ had been lost from the system since the onset of the Roche lobe overflow phase.

Moreover, the nebula is aligned with the jet-like structures inferred from recent optical measurements, indicating a possible connection among them.

Key words: stars: binaries: spectroscopic – stars: chemically peculiar – stars: individual: β Lyr

1. Introduction

β Lyrae ($3.4 \leq m_V \leq 4.4$, $P = 12.91^{\mathrm{d}}$) is a non-degenerate, semi-detached interacting binary system, located at a distance of 270$\pm$38 pc (Perryman et al. 1997). The primary component is a B6-8 II star in contact with its Roche lobe resulting in rapid mass transfer ($5 \times 10^{-5} M_{\odot}\mathrm{yr}^{-1}$) to its massive, unseen companion (Harmanec 1990). The nature of the secondary has been the subject of much speculation, from a flattened B5 star to a black hole with accretion disk. A B0V star embedded in a geometrically and optically thick accretion disk or a circumstellar shell, is currently the more favoured hypothesis (Hubeny & Plavec 1991, Harmanec 1992). The presence of circumstellar plasma surrounding both components is indicated by stationary optical and UV emission lines (Batten & Sahade 1973; Hack et al. 1975) as well as from the analysis of UV light curves (Kondo et al. 1994). Although β Lyrae has been observed extensively at other wavelengths for decades, radio observations are still too scarce to form a clear picture of its radio properties. The source was firstly detected by Wade & Hjellming (1972) at 2.7 and 8.1 GHz. During a successive monitoring program (Gibson 1975) the source always exhibited a spectrum consistent with thermal radio source with a radius ~ 50 AU, if a temperature of typical of an H II region (10^4 K) is assumed. However, Wright & Barlow (1975) have noted that the observed slope of the radio spectrum (α=0.96) is intermediate between that expected for a simple H II region and a stellar wind, implying that the physics underlying the radio emission of β Lyrae is more complicated than assumed in either of these models.

In an attempt to distinguish the various components of β Lyrae which may be contributing to the radio emission, we obtained high-spatial resolution radio maps of β Lyrae using MERLIN. In this paper we describe the results of these observations and briefly discuss their implications.

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2. Observations and results

We observed β Lyrae at 6 cm (4.994 GHz) using the Multi-Element Radio Linked Interferometer Network (MERLIN)[1] array on 1996 December 8, 9 and 16, from 04:00 to 22:00 UT.

The observations were performed in phase referencing mode, which is the standard MERLIN observing mode for weak sources. This technique allows a better calibration of phase variation by observations of a bright phase calibrator interleaved with the observations of the target source. The phase calibrator 1846+322 was used and the flux density scale was determined by observing 3C286, whose flux at 4.994 GHz is assumed to be 7.086 Jy.

Data were edited and amplitude calibrated using the OLAF software package. The phase calibration, mapping process and successive analysis were performed using the NRAO,

[1] MERLIN is a national facility operated by the University of Manchester at the Nuffield Radio Astronomy Laboratories, Jodrell Bank, on behalf of the Particle Physics and Astronomy Research Council (PPARC)

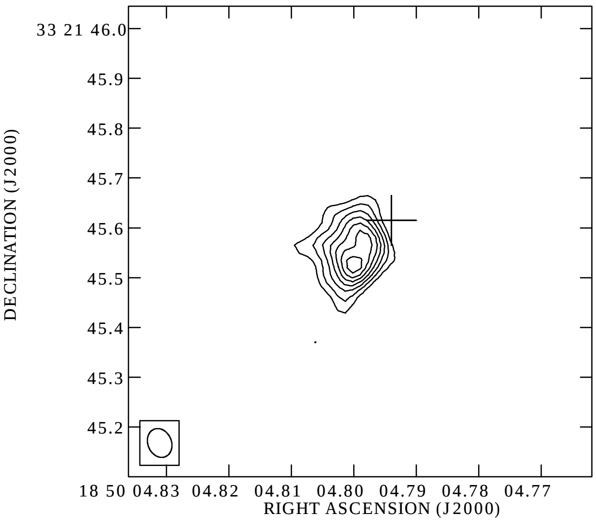

Fig. 1. The 6 cm radio map of β Lyrae. The contour plot shows the results of three separate 18 hour observations of β Lyrae combined into a single image. Levels of 0.18 (3σ), 0.24, 0.30, 0.36, 0.42, 0.48 and 0.54 mJy are shown. The position measured by Hipparcos is indicated with a large cross. The small inset ellipse is the half-power contour of the beam (60×47mas).

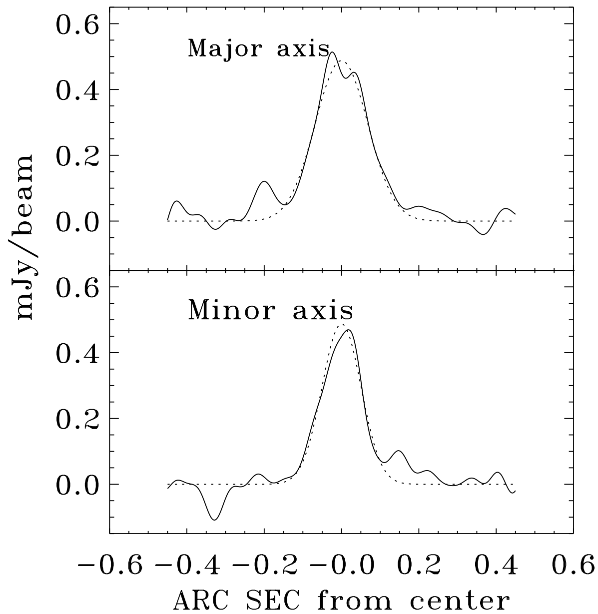

Fig. 2. Cross sections of the radio nebula along its principal axes (solid lines) together with the best fitting two dimensional Gaussian intensity distribution (dotted line).

Table 1. Parameters of the radio nebula around β Lyrae.

Parameter	Value
Flux density	3.2 ± 0.2 mJy
Size (FWHM)	$(145 \pm 12) \times (100 \pm 8)$ mas
Orientation (major axis)	$156.5° \pm 4°$
Radio position (J2000)	
RA	$18^h50^m04\overset{s}{.}800 \pm 0\overset{s}{.}0060$
Dec	$+33°21'45\overset{''}{.}554 \pm 0\overset{''}{.}004$
Epoch	1996.9
Optical position[a] (J2000)	
RA	$18^h50^m04\overset{s}{.}794 \pm 0\overset{s}{.}0002$
Dec	$+33°21'45\overset{''}{.}615 \pm 0\overset{''}{.}003$

[a] Hipparcos position reduced to same epoch including proper motion.

Astronomical **I**mage **P**rocessing **S**ystem. To achieve the highest possible signal-to-noise ratio the mapping process was performed using natural weighting and the CLEAN algorithm was used to extract information as close as possible to the theoretical noise limit.

We detected the source at all three epochs, corresponding to three different orbital phases. All three maps revealed a quite extended source, elongated slightly in the N-S direction. The noise level in the maps measured from several areas of blank sky is 6×10^{-5} Jy/beam, which is consistent with the expected theoretical noise. There are no significant differences between the maps observed at each epoch and so we combined the data from the three observing runs to form the radio map shown in Fig. 1.

The source morphology is dominated by a compact structure, aligned approximately N-S, probably ($< 3\sigma$ level), embedded in a more diffuse nebula. The profile of the radio nebula along its principal axes is shown in Fig. 2. From the figure is evident that most of the 6 cm emission comes from the central region, with negligible contribution from the more diffuse nebula, thus proving that a two dimensional Gaussian fit (dotted line) to the central part gives a fair description of the radio source.

The position, flux density and angular size of the source are thus derived by fitting the two dimensional Gaussian brightness distribution to the map. The values and their uncertainties, derived following Fomalont (1989), are given in Table 1. The optical position of β Lyrae reported by Hipparcos, allowing for the proper motion, is also given. Differences between radio and optical positions ($\Delta\alpha = 0.075''$, $\Delta\delta = -0.061''$) may be probably related to the overall position error to be associated to the source used as phase calibrator, reported to be of the order of $0.1''$ (Wilkinson et al. 1998).

MERLIN is sensitive to structures up to $3.5''$ at 6 cm. No structure is seen outside of the nebula up to these scales, which would suggest that all of the flux from the nebula is detected in these maps. The difference between the flux measured here and previous measurements (e.g. Mutel et al. 1985; Leone et al. 1994) is not surprising as β Lyrae is known to show variability at radio wavelengths.

3. Discussion and conclusions

The radio observations here discussed are direct confirmation of a large plasma cloud surrounding β Lyrae due to mass loss from the system. The angular size of the nebula corresponds to a linear size of approximately 40 AU, much larger than the binary system itself (~ 0.5 AU). As the source has been resolved we can derive a brightness temperature $T_{\rm B}$ as follows:

$$T_{\rm B} = \frac{1.36 \times 10^6 S \lambda^2}{\theta_1 \theta_2} \ {\rm K} = 11\,000 \pm 700 \ {\rm K} \qquad (1)$$

where S is the flux in mJy at the 5 GHz, λ is the observing wavelength in cm and θ_1 and θ_2 are the angular size of source in milliarcseconds. The derived brightness temperature implies a thermal origin for the radio emission.

It can be argued that the source has, in reality, a much more complex morphology that the present MERLIN observations can not resolve. If, for example, most of the flux is coming from two small components, with thus a much higher brightness temperature, the simple one-component model, we are assuming, will be no suitable. Still, in the former case, a higher brightness temperature would imply a non-thermal mechanism operating in the system. The presence of non thermal component has been inferred in about 30% of the early type radio emitting stellar systems (Bieging et al. 1989). All of these stars always exhibited spectral indices $\alpha \leq 0$ ($S_\nu \propto \nu^\alpha$), while past (Gibson, 1975) and more recent (Umana et al. 2000) radio observations of β Lyrae point out a thermal spectrum ($\alpha > 0$) for the system.

Jameson & King (1978) modelled the radio source associated to β Lyrae as a H II region. However, there is ample evidence, from both optical (Etzel & Meyer, 1983) and ultraviolet spectroscopy (Mazzali et al. 1992), of the presence of stellar wind in one or both components of the system, which can be responsible of the observed radio emission.

Mazzali et al. (1992) have developed a two-wind model to explain the peculiar UV spectrum of β Lyrae, consisting of "superionized" resonance lines, typical of hot-star winds, plus lines of moderately ionized species. The observed ultraviolet emission features can be modelled allowing the coexistence of two winds with different dynamical properties: a fast, but tenuous wind, associated to the hotter secondary component ($\dot{M}_{\rm h} = 5 \times 10^{-8} M_\odot {\rm yr}^{-1}$, $v_{\rm h} = 1470 \ {\rm km\,s^{-1}}$) and a denser, but slower wind, associated to the cooler B6-8 II primary ($\dot{M}_{\rm c} = 7.7 \times 10^{-7} M_\odot {\rm yr}^{-1}$, $v_{\rm c} = 390 \ {\rm km\,s^{-1}}$). Standard formulas for thermal radio emission from an expanding wind have been derived by Panagia & Felli (1975) and Wright & Barlow (1975). They showed that the observed radio flux (S) is related to the dynamical parameters of the wind through the relation:

$$S \propto \left(\frac{\dot{M}}{v_\infty} \right)^{4/3} \qquad (2)$$

where $\dot{M}$ and v_∞ represent the mass-loss rate and the terminal velocity of the wind.

We may ask under which conditions the thermal radio emission from the winds of the two early-type components of a binary system has the same radio properties as a single symmetric wind and thus the relation (2) can be applied.

The effects of binarity on thermal radio emission from early-type systems have been recently studied by Stevens (1995). Effects of possible interactions between winds, such as extra source of emission due to the shocked gas, are mostly function of the momentum ratio of the two winds and they would be negligible in systems, where one component has a dominant wind. The two-wind model outlined by Mazzali et al. (1992) foresees a case of a system when only one wind is dominant. Moreover, since the winds of the two stars will contribute to the measured flux according to the ratio of the relative factors ($\frac{\dot{M}}{v_\infty}$), allowing for difference in mass-loss and wind terminal velocity, this indicates that less than 0.5% of the observed flux is attributable to the BOV star's wind.

There is a class of stellar objects, the symbiotics, whose radio emission is interpreted in terms of a binary model, and where one of the two components has a dominant wind. Taylor & Seaquist (1984) attributed the observed radio emission to the stellar wind of the cool component of the system, which is ionized by the ultraviolet flux of the hot companion. They also showed that the geometry of the ionized radio emitting region of the intersystem material is determined by a single parameter, which is function of the physical parameters of the binary: separation (a), Lyman continuum luminosity of the hot component (L_{uv}), mass loss rate ($\dot{M}$) and velocity (v) of the dominant wind. If the wind is completely ionized, the ionized region shows the same radio properties as a spherically symmetric ionized wind. In the following we will check if this scenario is suitable also for β Lyrae.

By applying equation 14 from Taylor & Seaquist (1984) and assuming a binary separation of 61 solar radii (Harmanec, 1990), we obtain that the wind of the B6-8 II is completely ionized if

$$L_{uv} \geq 5.8 \times 10^{62} (\frac{\dot{M}}{v})^{-2} \sim 1.8 \times 10^{45} \ \ {\rm photons\,s^{-1}} \qquad (3)$$

where the values of $\dot{M}$ and v for the B6-8 II as determined by Mazzali et al. (1992) have been adopted. This requirement is well satisfied by the flux of Lyman continuum photons of the bright secondary component B0V, $L_{uv} = 4.26 \times 10^{47}$ photons s^{-1} (Panagia 1973), on the contrary of the B6-8 II, and we can safely apply relation (2).

This formula has been derived for the case of spherically symmetric winds. However, Schmid-Burgk (1982) showed that the mass loss rate derived from radio flux densities is quite insensitive to source geometry and only in very extreme cases of deviation from spherical symmetry a geometry-dependent correction factor must be applied. Thus even if the source morphology appears to be slightly elongated (axis ratio 1.45), we can use them quite confidently.

We, therefore, can estimate the mass loss by using the relation:

$$\dot{M} = 6.7 \times 10^{-4} v_\infty S_{\rm 6cm}^{3/4} D_{\rm kpc}^{3/2} (\nu \times g_{\rm ff})^{-0.5} \ \ M_\odot {\rm yr}^{-1} \qquad (4)$$

where full ionization and cosmic abundances have been assumed, v_∞ is the terminal velocity of the wind, $S_{\rm 6cm}$ the observed flux density at 6 cm in mJy, $D_{\rm kpc}$ the distance of the system, in kpc. $g_{\rm ff}$ represents the free-free Gaunt factor that, following Leitherer & Robert (1991), can be approximated with:

$$g_{\rm ff} = 9.77 (1 + 0.13 \log \frac{T^{3/2}}{\nu}) \qquad (5)$$

where T, in Kelvin, is the wind temperature.

By assuming the stellar wind velocity of the B6-8 II component ($v \sim 400 \text{ km s}^{-1}$, Mazzali et al. 1992) and constant temperature equal to the brightness temperature, derived by the present observations ($T = T_{\rm B}$), we obtain a mass loss rate of

$$\dot{M} = 5.6 \times 10^{-7} \ M_{\odot}{\rm yr}^{-1}. \quad (6)$$

This result is close to the value obtained by Mazzali et al. (1992) for the B6-8 II component by modelling UV spectral lines, i. e. $7.16 \times 10^{-7} \ M_{\odot}{\rm yr}^{-1}$ and indicates that the wind associated to the primary is predominant in the replenishment of the circumsystem material and constitutes the bulk of the system's mass loss.

β Lyrae is approaching the end of a phase of strong mass transfer between components, which started 26000 years ago (De Greve & Linnell 1994). The presence of such a nebula is the proof that the system had evolved in a non conservative way, i. e., with a fraction of the material from the loser lost by the system. This was already foreseen by the evolutionary studies of De Greve & Linnell (1994) since their conservative solution lead to several discrepancies with the observed characteristics of the system.

If we assume that during this phase of mass transfer the mass-loss rate was constant ($5.6 \times 10^{-7} M_{\odot}{\rm yr}^{-1}$) we estimate that almost 0.015 $M_{\odot}$ should have been lost by the system.

High resolution optical interferometry combined with extensive photometry and spectroscopy has led Harmanec et al. (1996) to conclude that β Lyrae contains jet-like structures perpendicular to the orbital plane which are responsible for the bulk of the Hα and He I 6678 emission. This scenario, already proposed by Harmanec (1992), is further supported by recent spectropolarimetric observations of Hoffman et al. (1998), who suggested the presence of a bipolar outflow in β Lyrae , perpendicular to the orbital plane (P.A. = $164°$) and probably associated to the accretion disk around the mass-gaining component.

The radio image presented in this work gives a hint of structure within the nebula, even if the obtained angular resolution did not allow us to trace the structure of the star's circumstellar matter at very small scale and thus to verify the association of the radio emitting features to the bipolar optical jets. One piece of information on this direction, provided by the present results, is that the radio nebula is almost exactly aligned with these optical jet-like structures (P.A. = $156.5° \pm 4°$).

It may be more accurate to picture the outflow as a stellar wind collimated by the thick accretion disk. The appearance of the circumbinary material would thus consist of a more extended component, due to the mass-loss from the system as a whole, plus an inner more compact component, related to the accretion disk created in the process of mass transfer from the B star to the hidd en companion.

To establish the feasibility of this scenario high resolution radio observations, at frequencies higher than 5 GHz, aimed to probe the morphology of the inner structure of the radio nebula are necessary. This observations, by allowing to look more inside the binary's outflow, would provide further insight into the formation of the circumstellar matter and are of particular importance in understanding the connection of the observed radio nebula to the bipolar optical jets reported by Harmanec et al. (1996) and Hoffman et al. (1998).

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References

Batten A.H., Sahade J., 1973, PASP 85, 599
Bieging J.H., Abbott D.C., Churchwell E., 1989, ApJ 340, 518
De Greve J.P., Linnell A.P., 1994, A&A 291, 786
Etzel P.B., Meyer D.M., 1983, PASP 95, 891
Fomalont E.B., 1989, In: Perley R.A., Schwab F.R., Bridle A.H. (eds.) Proc. ASP Conf. Ser. Vol. 6, Synthesis imaging in Radio Astronomy. Image Analysis. p. 213
Gibson D.M., 1975, Ph D. Thesis, University of Virginia
Hack M., Hutchings J.B., Kondo Y., et al., 1975, ApJ 198, 453
Harmanec P., 1990, A&A 237, 91
Harmanec P., 1992, A&A 266, 307
Harmanec P., Morand F., Bonneau D., et al., 1996, A&A 312, 879
Hoffman J.L., Nordsieck K.H., Fox G.K., 1998, AJ 115, 1576
Hubeny I., Plavec M.J., 1991, AJ 102, 1156
Jameson R.F., King A.R., 1978, A&A 63, 285
Kondo Y., McCluskey G.E., Silvis J.M.S., et al., 1994, ApJ 421, 787
Leitherer C., Robert C., 1991, ApJ 377, 629
Leone F., Trigilio C., Umana G., 1994, A&A 283, 908
Mazzali P.A., Pauldrach A.W.A., Puls J., Plavec M.J., 1992, A&A 254, 241
Mutel R.L., Lestrade J.F., Preston R.A., Phillips R.B., 1985, ApJ 289, 262
Panagia N., 1973, AJ 78, 929
Panagia N., Felli M., 1975, A&A 39, 1
Perryman M.A.C., Hog E., Kovalevsky J., Lindgreen L., Turon C., 1997, The *Hipparcos* and Tycho Catalogs. ESA SP-1200
Stevens I.R., 1995, MNRAS 277, 163
Schmid-Burgk J., 1982, A&A 108, 169
Taylor A.R., Seaquist E.R., 1984, ApJ 286, 263
Umana G., Trigilio C., Leone F., 2000, in preparation
Wade C.M., Hjellming R.M., 1972, Nat 235, 270
Wilkinson P.N., Browne I.W.A., Patnaik A.R., Wrobel J.M., Sorathia B., 1998, MNRAS 300, 790
Wright A.E., Barlow M.J., 1975, MNRAS 170, 41