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A first orbital solution for the non-thermal radio emitter Cyg OB2 #9*

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Abstract: We reported in 2008 the first detection of the binary nature of Cyg OB2 #9. Since then, we have continued our spectroscopic monitoring of this object, doubling the number of available spectra of the star while covering a second periastron passage. Using a variety of techniques, the radial velocities were estimated and a first, preliminary orbital solution was derived (P=2.4 yrs). The mass ratio appears close to unity and the eccentricity is large, 0.7-0.75.

1 Introduction

Non-thermal radio emission is a rare phenomenon among massive stars, with fewer than 40 cases known in our Galaxy (see e.g. De Becker 2007). It requires two ingredients, magnetic fields and relativistic electrons. Magnetic fields have long been searched for in massive stars, but it is only in the last decade that the first direct detections were finally obtained from sensitive spectropolarimetric observations (e.g. Donati et al. 2002, Hubrig et al. 2008). A population of relativistic electrons can be generated from shocks through the first-order Fermi mechanism and the stellar winds of massive stars are good places to find such shocks. Indeed, on the one hand, the line-driving mechanism at the origin of the wind acceleration is intrinsically unstable; on the other hand, shocks can also appear when winds collide in massive binaries. Theoretical modelling showed that the observed non-thermal radio emission can be reproduced only in the second case, i.e. in colliding wind binaries (Van Loo et al. 2005). Dedicated observational campaigns confirm this view by revealing signatures of multiplicity in most non-thermal radio emitters — only 3 of the 17 WRs and 3 of the 16 O stars listed by De Becker (2007) totally lacked evidence for binarity.

One of these remaining cases is Cyg OB2 #9, though it was one of the first O-stars detected as a non-thermal radio emitter (Abbott et al. 1984). It was only in 2008 that two pieces of evidence finally

*Based on data obtained with XMM-Newton (ESA) and at the OHP (France).
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pointed towards a binary scenario. The first one was indirect: a long-term (2.355 yrs) modulation of the radio emission was detected by Van Loo et al. (2008). The second piece of evidence was the unambiguous detection of double line profiles in the optical spectrum of Cyg OB2 #9 by Nazé et al. (2008). However, no orbital solution could then be derived and the direct detection of wind-wind collision (e.g. through X-ray data) was still lacking.

2 Optical data

2.1 Observations

In the last decade, we began an intensive spectroscopic monitoring of Cyg OB2 #9. To investigate the binarity of the star, spectral resolving powers of at least 3500 (and maximum 35 000) were required and the yellow-red domain was favored due to the high interstellar extinction. These data were obtained at the Asiago observatory (AFOSC in echelle mode), San Pedro Mártir Observatory (Espresso), Wyoming Infrared Observatory (WIRO-Longslit spectrograph), and the Haute-Provence Observatory (Aurélie and Sophie spectrographs). Exposure times of several hours were often needed to reach typically signal-to-noise ratios of 50–100. The wavelength calibration was improved by using strong and narrow diffuse interstellar bands close to stellar lines, remaining errors on the radial velocities (RVs) being reduced to $<$5–10 km s^{-1}. A full journal of the observations can be found in Nazé et al. (2008, 2010).

2.2 A preliminary orbit

Cyg OB2 #9 is not an easy star to analyse since it is strongly absorbed. The star therefore appears faint and its optical spectrum is filled with strong interstellar lines, often more intense than the stellar lines. To get reliable RVs, the best choice is He I λ 5876 since it is a stellar line which is both strong and uncontaminated by interstellar components (there is a caveat, though, since this line sometimes appears polluted by emission in some extreme O-type stars but we do not see obvious emission in our dataset). In total, our monitoring provided 34 observations of that line.

Another problem is that the stellar lines appear blended during 80% of the orbit. Several ways to determine the RVs were therefore tested. Cross-correlations, line disentangling, and 2-Gaussian fitting throughout the whole orbit give poor results, due to the strong line blending. Reliable RVs could then be found from two methods only. The first one is to find the individual line properties from a 2-Gaussian fitting when the lines are at maximum separation and then to fix the line characteristics (width, intensity), shifting the resulting Gaussians until the χ^2 is minimized (case A in Table 1 below). The second method is to perform 2-Gaussian fitting when the lines appear somewhat deblended (20% of the orbit) and 1-Gaussian fitting otherwise (case B in Table 1 below). This latter solution is probably less reliable than the former one, but it relies on fewer assumptions and thus represents a "minimalistic" approach.

Once a reliable set of RVs was available, a period search was performed using the Heck et al. (1985) Fourier method. The SB2 dataset was then converted into an equivalent SB1 dataset (cf. Liège Orbital Solution Package, Sana & Gosset, A&A, submitted). A first guess of the orbital solution was then derived from the Wolfe et al. (1967) or Lehmann-Filhés (1894) methods, the final solution being found after a Levenberg-Marquardt minimization. An independent check was made using the method of Zechmeister & Kurster (2009). Table 1 provides the orbital solutions derived from the two RV datasets considered above.

The period derived from the optical data is fully compatible with the timescale derived from the recurrent radio variations. The mass ratio is close to unity, confirming the preliminary results of

Table 1: Preliminary orbital solution of Cyg OB2 #9. Solution A uses RVs determined using the χ^2 method, solution B uses 2 RVs only when the lines are clearly deblended. Note that T_0 is expressed as HJD - 2 450 000 and that the preferred inclination is ~50° for case A and ~70° for case B (if both stars are supergiants and the "typical" masses of O5–7 stars from Martins et al. 2005 are assumed).

Parameter	A	B
P(d)	852.9±4.3	852.8±4.4
T_0	4036.8±3.69	4030.9±3.9
e	0.744±0.0304	0.708±0.027
$\omega(°)$	−164.4±4.19	−175.1±4.4
M_1/M_2	1.17±0.22	1.10±0.17
γ_1(km s^{-1})	−40.6±3.23	−28.1±3.4
γ_2(km s^{-1})	16.6±3.5	1.2±3.5
K_1(km s^{-1})	53.0±7.0	63.2±6.8
K_2(km s^{-1})	62.1±8.1	69.4±7.4
$a_1 \sin i$(R$_\odot$)	598.0±84.4 7	752.1±86.0
$a_2 \sin i$(R$_\odot$)	699.3±97.7 3	825.9±93.7
$M_1 \sin^3 i$(M$_\odot$)	21.7±7.2	38.0±10.1
$M_2 \sin^3 i$(M$_\odot$)	18.6±6.1	34.6±9.1
rms(km s^{-1})	14.5	16.3

Nazé et al. (2008), who proposed spectral types of O5 and O6–7 for the binary components. The eccentricity is large, but is not the main cause of the poor deblending. In fact, the non-crossing of the RV curves (see Fig. 1) comes mostly from the large asymmetry in the center-of-mass velocities (often attributed to wind asymmetries and/or illumination effects on the side of the star facing its companion, see Rauw et al. 1996 and references therein). While non-equal γ are often observed in massive binaries, Cyg OB2 #9 clearly appears as an extreme case, at least as far as O-type binaries are concerned.

3 X-ray data

The Cyg OB2 association was observed six times with the XMM-Newton observatory: four pointings (with a separation of 10 days) were obtained in Oct.-Nov. 2004 and two pointings, separated by 4 days, were taken in May 2007. The data reduction and instrumental configuration were similar in all cases. The stellar data were always extracted in a circle of at least 23″ in radius while the background was estimated from a nearby source-free region some $50'' \times 20''$ in size. Considering the ephemeris of Cyg OB2 #9 derived above, these X-ray data correspond to orbital phases of 0.14–0.18 for the 2004 data and of 0.21–0.22 for the 2007 data.

The X-ray spectrum of Cyg OB2 #9 appears thermal in nature, as evidenced by the presence of several X-ray lines (notably the iron line at 6.7 keV, Fig. 2). No trace of non-thermal emission is detected but this is not surprising, as the strong thermal emission can easily hide any non-thermal X-ray emission in the 1–10 keV range (see e.g. De Becker et al. 2009).

Good fits are obtained with models using two thermal components, both being absorbed by the (fixed) interstellar absorption and an additional wind component let free to vary. In all six cases, the derived spectral parameters are rather similar: the wind absorbing column amounts to $\sim 5 \times 10^{21}$ cm^{-2}, while the two temperatures are 0.6 keV and ~2.4 keV. In fact, the spectrum is similar to that of HD168112, another non-thermal radio emitter. The $\log(L_X/L_{BOL})$ ratio amounts to −6.3

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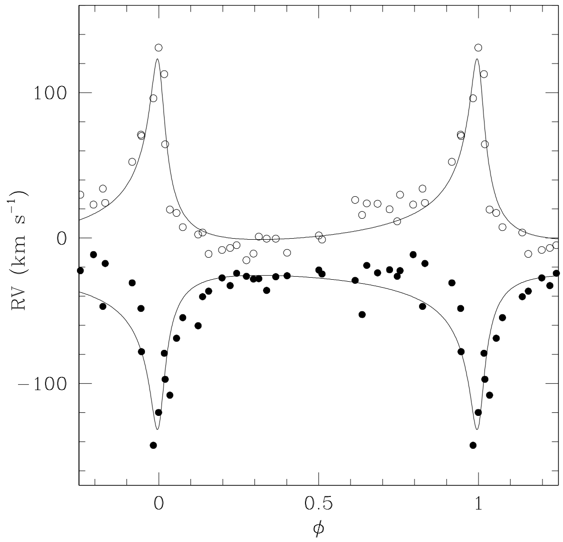

Figure 1: RV curves superimposed on the best SB2 solution (case A). Figure reproduced from Nazé et al. (2010).

and the average temperature $< kT >$ is 1.2 keV. Comparing with the results from the 2XMM survey (Nazé 2009), Cyg OB2 #9 therefore appears slightly overluminous (it is on the luminous edge of the $\log(L_X/L_{BOL})$ dispersion for O-type stars) and somewhat hot (in the 2XMM, 83% of the O-type stars display $< kT >$ below 1 keV). However, there is no strong signature of colliding winds in our XMM data.

Nonetheless, an intriguing fact is the detection of some variability between exposures (Fig. 2). There is notably a 10% decrease of the flux between 2004 and 2007, i.e. as the stars get further away from each other. This flux decreases towards apastron and the lack of strong colliding winds signature in the available data may be reconciliable with a colliding winds scenario — there would be an intense brightening near periastron, followed by a decrease and a minimum contamination of the wind-wind collision emission near apastron. However, this needs to be ascertained by securing data near periastron.

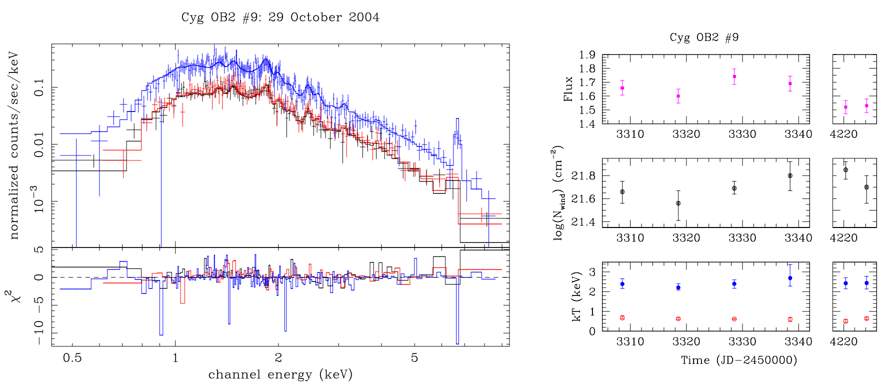

Figure 2: Left: EPIC spectra of Cyg OB2 #9 with best-fit model superimposed (lower/upper data points correspond to EPIC-MOS/pn, respectively). Right: Variations of the fitted parameters through the observations. Figure reproduced from Nazé et al. (2010).

4 Conclusions

Thanks to an intensive optical spectroscopic monitoring, we have obtained the first orbital solution for Cyg OB2 #9. This system has a long period ($\sim$850d), a mass ratio close to unity, and a large eccentricity ($\sim$0.7). It is a difficult system to study, as the lines are deblended only in a small window of the orbit, implying that the center-of-mass velocities are very different from each other, which could be linked to the illumination of one star by the other and/or wind asymmetries.

In the X-ray domain, Cyg OB2 #9 is only slightly harder and brighter than "normal" O-type stars, i.e. no strong emission from the expected wind-wind collision is detected. Some low-amplitude (10%) flux variability is however detected, but its origin is uncertain without additional data (it must be noted that the observations were all taken quite close to each other and relatively far from periastron).

The next periastron passage should occur in mid-2011. We plan to perform a multiwavelength monitoring (from X-ray to radio) at that time, in order to ascertain the full geometry of the colliding winds' zone and the full orbital characteristics. Only then will a detailed hydrodynamical modelling be possible, which should shed new light on non-thermal emission processes in O-type stars.

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