

# Discovery of a parsec-scale bipolar nebula around MWC 349A

V. V. Gvaramadze<sup>1,2,3</sup> and K. M. Menten<sup>4</sup>

<sup>1</sup> Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany  
e-mail: vgvaram@mx.iki.rssi.ru

<sup>2</sup> Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskij Pr. 13, 119992 Moscow, Russia

<sup>3</sup> Isaac Newton Institute of Chile, Moscow Branch, Universitetskij Pr. 13, 119992 Moscow, Russia

<sup>4</sup> Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, Bonn 53121, Germany  
e-mail: kmenten@mpi-fr-bonn.mpg.de

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## ABSTRACT

We report the discovery of a bipolar nebula around the peculiar emission-line star MWC 349A using archival *Spitzer* Space Telescope 24  $\mu\text{m}$  data. The nebula extends over several arcminutes (up to 5 pc) and has the same orientation and geometry as the well-known subarcsecond-scale ( $\sim 400$  times smaller) bipolar radio nebula associated with this star. We discuss the physical relationship between MWC 349A and the nearby B0 III star MWC 349B and propose that both stars were members of a hierarchical triple system, which was ejected from the core of the Cyg OB2 association several Myr ago and recently was dissolved into a binary system (now MWC 349A) and a single unbound star (MWC 349B). Our proposal implies that MWC 349A is an evolved massive star (likely a luminous blue variable) in a binary system with a low-mass star. A possible origin of the bipolar nebula around MWC 349A is discussed.

**Key words.** stars: individual: MWC 349A – stars: winds, outflows – stars: massive – binaries: general – circumstellar matter

## 1. Introduction

MWC 349A is a curious star located on the sky in the direction of the Cyg OB2 association. It was identified as a peculiar emission-line star in 1932 by Merrill et al. (1932), who also noted the presence of a second star, MWC 349B,  $\approx 2$  arcsec west. Since that time MWC 349A attracted wide attention and although many interesting details have been revealed about it, the nature of this star remains puzzling.

MWC 349A is one of the brightest radio stars on the sky (Braes et al. 1972). Its radio emission was resolved with the Very Large Array (VLA) in a sub-arcsecond square nebula by Cohen et al. (1985), who suggested that the shape of the nebula might be due to a biconical outflow of ionized gas pinched at the waist by a disk seen edge-on and oriented due east-west. This suggestion was confirmed by White & Becker (1985), whose higher resolution and higher frequency data clearly revealed an hourglass-shaped bipolar nebula with a symmetry axis almost in the north-south direction (see also Tafoya et al. 2004). MWC 349A also known as a source of hydrogen (sub)millimeter recombination lines that show maser (Martín-Pintado et al. 1989) and laser action (Strel'nitski et al. 1996). With increasing frequency, these lines attain a more and more pronounced two-peaked profile that was interpreted as originating from a disk or ring-shaped structure in Keplerian rotation around the central star of mass of  $\sim 30 M_{\odot}$  (Thum et al. 1992; Ponomarev et al. 1994). (Sub)millimeter interferometry showed the emission to be consistent with a disk (Planesas et al. 1992), but revealed a velocity structure not consistent with Keplerian, which prohibits a mass estimate for the central object (Weintraub et al. 2008).

Cohen et al. (1985) found a signature of interaction between the nebula and MWC 349B and suggested that this star forms a binary system with MWC 349A (see also Tafoya et al. 2004).

Cohen et al. (1985) were also able to separate the spectra of the two stars and classified MWC 349B as a B0 III star. The spectrum of MWC 349A is dominated by a multitude of very strong emission lines, which completely hide the photospheric lines (Cohen et al. 1985; Andrillat et al. 1996) and make a spectral classification of the star impossible. Using the spectral type of MWC 349B, Cohen et al. (1985) estimated a distance to the putative binary system of 1.2 kpc, which is much smaller than the distance to Cyg OB2 accepted at this time, i.e., 2 kpc. The physical relationship between MWC 349A and MWC 349B was questioned by Meyer et al. (2002). These authors measured polarization towards the two stars and found that MWC 349B is more highly polarized than MWC 349A. On the other hand, they found that several members of Cyg OB2 near to MWC 349A have polarization characteristics similar to those of the interstellar polarization towards this star. Based on these findings, Meyer et al. (2002) suggested that MWC 349A and MWC 349B are members of the Cyg OB2 association and that they are projected by chance near the same line of sight, with MWC 349B located “behind the dusty region around MWC 349A”. Meyer et al. (2002), however, did not explain how to reconcile the distances to Cyg OB2 and MWC 349B. The problem of the physical relationship between MWC 349A and MWC 349B is very important for understanding the nature of the former star. If both stars form a binary system, then MWC 349A should be a massive evolved star, while the distance to the system should be equal to the spectroscopic distance to MWC 349B. In Sect. 3 we argue that both stars could indeed reside in the Cyg OB association and at the same time they could be physically related to each other (at least in the recent past).

The bipolar radio nebula associated with MWC 349A is produced by a constant velocity outflow of ionized gas (Olson 1975; Hartmann et al. 1980). Widths of the [N II]  $\lambda 6584$  emission line

(Hartmann et al. 1980) and the hydrogen radio recombination lines (Altenhoff et al. 1981) suggest that the velocity of the outflow is  $\sim 50 \text{ km s}^{-1}$ . Hartmann et al. (1980) argued that the low-velocity nature of the wind could be understood if the star has a low effective surface gravity (i.e. the star is inflated) and interpreted MWC 349A as a supergiant star of P Cygni type. Radio continuum observations indicate an outflow mass-loss rate of  $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$  (Hartmann et al. 1980; Altenhoff et al. 1981; Dreher & Welch 1983). With this mass-loss rate and the low wind velocity the line emission in the optical and the near-infrared must become optically thick if the outflow originates at a radius of  $\lesssim 1 \text{ AU}$  (Altenhoff et al. 1981). Since the emission lines appear to be optically thin (Thompson et al. 1977), it was suggested that the outflow is fed by a circumstellar disk, so that the velocity of the wind is rather set by the escape velocity from the disk than by that from the stellar surface (Altenhoff et al. 1981). The presence of a (nearly edge-on) circumstellar disk also allows one to explain the coexistence of low- and high-excitation emission lines in the spectrum of MWC 349A (Hamann & Simon 1986), the double-peaked profiles of optical, infrared (Hamann & Simon 1986, 1988) and masing (Planesas et al. 1992; Thum et al. 1992; Gordon 1992) emission lines, and the high level of polarization in this star (Elvius 1974; Yudin 1996; Meyer et al. 2002). The existence of the disk was confirmed with infrared speckle interferometry (Leinert 1986; Danchi et al. 2001; Hofmann et al. 2002), which revealed a flattened structure (with a major axis of  $\approx 60 \text{ mas}$  or  $\approx 85 \text{ AU}$  at our adopted distance of 1.4 kpc; see Sect. 3.1) lying in the east-west plane, i.e. oriented perpendicular to the symmetry axis of the bipolar radio nebula. It is widely accepted that the disk plays a crucial role in formation and shaping the radio nebula, whose extent along the polar axis (as seen in the VLA 2 cm image; see Sect. 2.2) is  $\approx 1000 \text{ AU}$  or  $\approx 0.005 \text{ pc}$ .

In this paper, we report the discovery of a parsec-scale mid-infrared bipolar nebula around MWC 349A, whose orientation and geometry are similar to those of the sub-arcsecond radio nebula. The close similarity of the morphologies of the two nebulae suggests that they are shaped by the same agent – the disk around MWC 349A. The newly-discovered nebula is presented in Sect. 2. In Sect. 3 we discuss the location and the evolutionary status of MWC 349A, the possible origin of the bipolar outflow associated with this star, and the similarity between this outflow and bipolar nebulae produced by other massive evolved stars. We summarize in Sect. 4.

## 2. Mid-infrared, radio and $H\alpha$ nebulae around MWC 349A

### 2.1. *Spitzer* data

The large-scale infrared nebula around MWC 349 was detected in archival data originating from observations of the *Spitzer* Space Telescope, namely within the framework of the Cygnus-X *Spitzer* Legacy Survey (Hora et al. 2008)<sup>1</sup>. This survey covers 24 square degrees in Cygnus X, one of the most massive star-forming complexes in the Milky Way (e.g., Piddington & Minnett 1952; Reipurth & Schneider 2008), and provides images at 24 and  $70 \mu\text{m}$  obtained with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) and at 3.6, 4.5, 5.8, and  $8.0 \mu\text{m}$  obtained with the Infrared Array Camera (IRAC; Fazio et al. 2004). The resolution of the MIPS 24 and  $70 \mu\text{m}$  images is  $\approx 6$  and 18 arcsec, respectively, while that of

the IRAC images is  $\approx 1$  arcsec. Inspection of the data from this survey have already led to the discovery of a new Wolf-Rayet star (through the detection of a circular  $24 \mu\text{m}$  shell and follow-up spectroscopy of its central star; Gvaramadze et al. 2009) and a second (concentric) shell around the already known infrared shell (Trams et al. 1998; Egan et al. 2002) surrounding the candidate luminous blue variable (cLBV) star GAL 079.29+00.46 (Gvaramadze et al. 2010a; Jiménez-Esteban et al. 2010; Kraemer et al. 2010). The MIPS and IRAC post-basic calibrated data on MWC 349A were retrieved from the NASA/IPAC Infrared Science Archive<sup>2</sup>. Like many other circumstellar nebulae discovered with *Spitzer* (e.g. Gvaramadze et al. 2010a; Wachter et al. 2010; Mizuno et al. 2010), the nebula associated with MWC 349A is best visible at  $24 \mu\text{m}$ . It can also be seen at  $70 \mu\text{m}$ , but in none of the IRAC images.

The left and the middle panels of Fig. 1 present the MIPS 24 and  $70 \mu\text{m}$  images of the nebula and its central star MWC 349A (a white dot at the centre of the star in the MIPS  $24 \mu\text{m}$  image is due to saturation effect). At  $24 \mu\text{m}$  the nebula has a pronounced bipolar (hourglass-like) structure stretched almost in the north-south direction. The waist of the nebula is surrounded by a bright belt with a diameter of  $\approx 2.7$  arcmin. The nebula is somewhat asymmetric with respect to the polar axis. From the west side the lobes are outlined by almost straight filaments, with the northern and the southern ones extended, respectively, out to  $\approx 5.5$  and 6 arcmin from the waist. From the east side, the lobes are bounded by somewhat curved filaments. The northern filament extends out to  $\approx 3$  arcmin from the waist and then merges with the bright background, while the southern one can be traced up to  $\approx 7$  arcmin. The curvature of the latter filament suggests that the southern lobe might be a closed structure.

At  $\approx 2$  arcmin from the waist the eastern filament of the southern lobe splits into two parts and becomes concave towards the interior of the lobe, which might indicate an interaction between the laterally expanding nebula and the ambient medium. At our adopted distance of 1.4 kpc (see Sect. 3.1), 1 arcmin corresponds to  $\approx 0.4 \text{ pc}$ , so that the diameter of the waist is  $\approx 1.1 \text{ pc}$ , while the lobes stretch out to  $\approx 2.4\text{--}2.8 \text{ pc}$  from the equatorial belt. Interestingly, MWC 349A is offset by  $\approx 20$  arcsec (or  $\approx 0.14 \text{ pc}$ ) from the geometric centre of the waist, being closer to its eastern edge. This displacement could be understood if the nebula impinges on a more dense ambient medium in the eastern direction. The presence of the dense material on the eastern side of the nebula might be inferred from the  $70 \mu\text{m}$  and the 17 cm radio wavelength (see Sect. 2.2) images of the field around the nebula (see the middle and the right panels of Fig. 1, respectively). The  $70 \mu\text{m}$  image also shows obvious counterparts to the equatorial belt and the eastern boundary of the southern lobe.

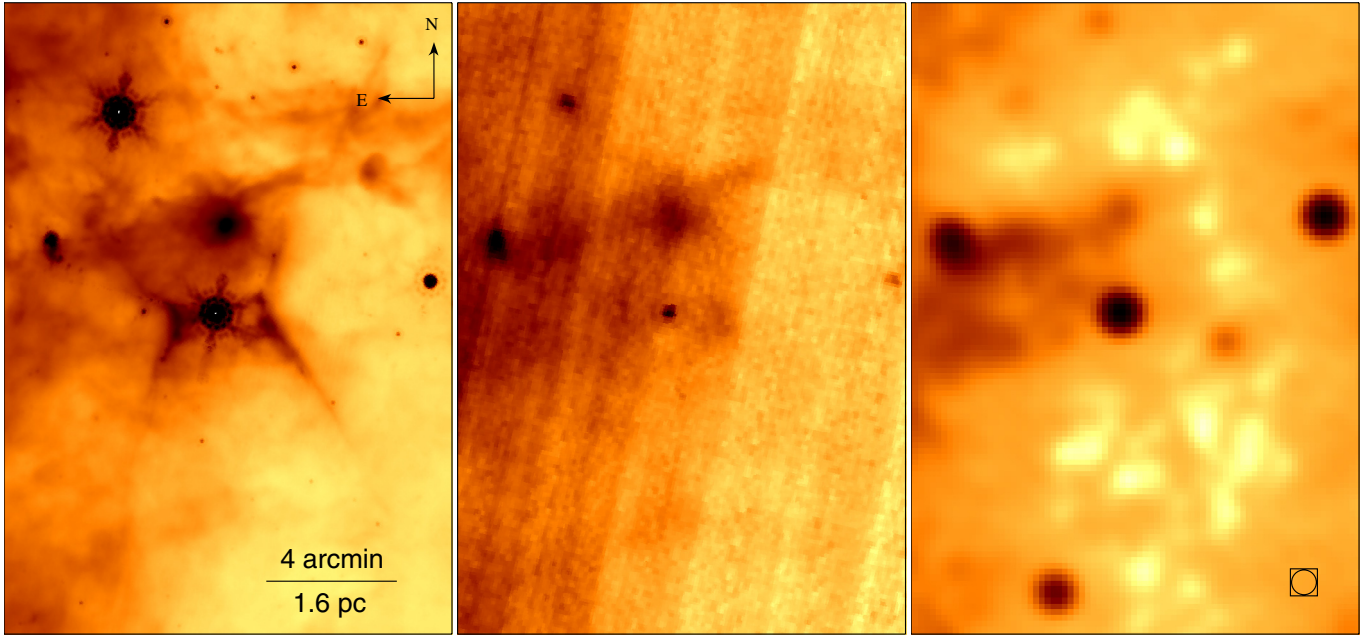
### 2.2. VLA data

To produce a long wavelength (*L*-band,  $\approx 17 \text{ cm}$ ) radio image of MWC 349A, we used two archival datasets obtained with the NRAO Very Large Array (VLA)<sup>3</sup>. The datasets were acquired and calibrated by R. Perley in the course of a long-range monitoring campaign. The data were taken on 2008 August 31 in the most compact (D) configuration at 1665.9 and 1875.1 MHz, each with one intermediate frequency band with bandwidth 12.5 MHz. The data were processed further with programs of

<sup>2</sup> <http://irsa.ipac.caltech.edu/>

<sup>3</sup> The VLA is operated by the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

<sup>1</sup> <http://www.cfa.harvard.edu/cygnusX>



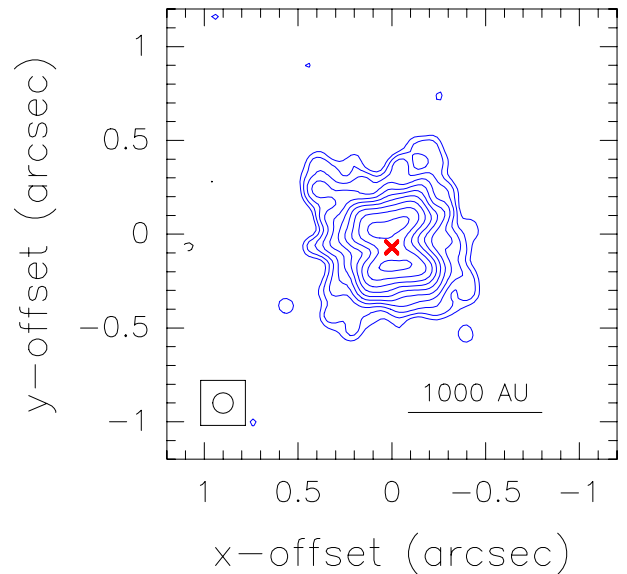
**Fig. 1.** *Left:* MIPS  $24\mu\text{m}$  image of the arcminute-scale bipolar nebula and its central star MWC 349A (a bright source in the waist of the nebula; note that a white dot at the centre of this source is due to saturation effect). *Middle and right:* MIPS  $70\mu\text{m}$  and VLA 17 cm images of the same field. The  $47''$  FWHM restoring beam is represented in the bottom right corner of the radio image.

the Astronomical Image Processing System (AIPS) in the usual manner. First, the two datasets were combined (using DBCON) and then imaged with IMAGR. One cycle of self-calibration (with CALIB) improved the image quality. The image, part of which is presented in Fig. 1, was restored with a circular Gaussian beam with FWHM  $47''$ . There are no clear indications of the presence of radio emission associated with the mid-infrared nebula.

We also produced a radio image of MWC 349A with higher resolution taken in the most extended (A) configuration at a shorter wavelength (*U*-band, 2 cm) from archival data taken on 1983 October 30 at a frequency of 14.94 GHz. The observations are reported and discussed by White & Becker (1985) and we refer to this publication for details on the data and their processing. Additional use of self-calibration resulted in an improved image. This image (presented in Fig. 2) shows the well-known subarcsecond-scale radio nebula associated with MWC 349A. Comparison of Fig. 2 with the MIPS  $24\mu\text{m}$  image of the arcminute-scale nebula shows that both nebulae have the same orientation and bipolar morphology. Note that by coincidence the angular size of the field shown in Fig. 2 turns out to be equal to that of the saturated pixel (the white dot) in the very centre of the  $24\mu\text{m}$  image of MWC 349A.

### 2.3. $H\alpha$ data

The parsec-scale nebula around MWC 349A was also detected in the  $H\alpha$  narrow-band CCD imaging survey of B[e] stars by Marston & McCollum (2008). These authors noted that “an apparent thin shell of approximately  $2.5$  diameter exists around MWC 349A to the north”. Comparison of their Fig. 4a with the  $24\mu\text{m}$  image in Fig. 1 shows that a thin  $H\alpha$  filament west of MWC 349A coincides with the western edge of the equatorial belt, while an arc-like diffuse  $H\alpha$  emission to the east shows a good correspondence with the eastern edge of the waist.



**Fig. 2.** VLA 2 cm image of the subarcsecond bipolar nebula around MWC 349A (indicated by a cross). The angular size of the field shown in this figure is equal to that of a white spot in the centre of the  $24\mu\text{m}$  image of MWC 349A (see the left panel of Fig. 1). The  $0.11''$  FWHM restoring beam is represented in the bottom left corner.

### 3. Discussion

Above we have reported the discovery of a parsec-scale mid-infrared nebula around the enigmatic emission-line star MWC 349A, whose hourglass-like structure and orientation are similar to those of the well-known subarcsecond radio nebula associated with this star. The morphology of the nebula is very similar to that of some planetary nebulae (e.g. the Engraved Hourglass Nebula; Sahai et al. 1999), nebulae around symbiotic systems (e.g. the Southern Crab Nebula; Corradi & Schwarz 1993), and nebulae associated with young stellar objects (e.g.

the disk/outflow radio source I in the Kleinmann-Low Nebula in Orion; Plambeck et al. 2009; Matthews et al. 2010) and some evolved massive stars (e.g. the cLBV Sher 25, Brandner et al. 1997, and the famous LBV  $\eta$  Carinae). Correspondingly, three main interpretations of the subarcsecond bipolar nebula associated with MWC 349A were proposed: (i) planetary nebula (Ciatti et al. 1974), (ii) photo-evaporation induced outflow from an accretion disk around a massive pre-main sequence star (e.g. Thompson et al. 1977), and (iii) outflow from an (excretion) disk around an evolved massive star (Hartmann et al. 1980).

Hofmann et al. (2002) thoroughly analysed these three possibilities and came to the conclusion that MWC 349A is most likely an evolved massive star (a B[e] supergiant) residing in the Cyg OB2 association. Similar proposals on the evolutionary status of MWC 349A were also put forward by Swings & Struve (1942), Baldwin et al. (1973), Hartmann et al. (1980), Herzog et al. (1980), Andrillat et al. (1996), and Lamers et al. (1998). The membership of the Cyg OB2 association seems, however, to be at variance with the possibility that MWC 349A forms a physical system with MWC 349B (Cohen et al. 1985; Tafoya et al. 2004), since the spectroscopic distance to the latter star of  $\sim 1.2$  kpc is significantly smaller than the today's widely accepted distance to Cyg OB2 of 1.7 kpc (Knödlseider 2000; Reipurth & Schneider 2008). Before discussing the possible origin of the bipolar nebula associated with MWC 349A, we have to understand whether the physical relationship between the two stars could be consistent with their membership of the Cyg OB2 association.

### 3.1. Birth cluster and the evolutionary status of MWC 349A

Let us assume that MWC 349A is a massive evolved star as argued by Hofmann et al. (2002). In this case, the question about the birth cluster of this star arises. Indeed, there is growing acceptance that most (or probably all) massive stars are formed in the clustered way (Lada & Lada 2003) and subsequently found themselves in the field either because of dynamical few-body encounters in the parent clusters, binary-supernova explosions and/or due to rapid cluster dissolution (e.g., Kroupa & Boily 2002; de Wit et al. 2005; Schilbach & Röser 2008; Gvaramadze & Bomans 2008b; Pflamm-Altenburg & Kroupa 2010; Gvaramadze et al. 2010b; Weidner et al. 2011)<sup>4</sup>. One can therefore expect that the parent cluster of MWC 349A should be nearby, unless this star is a high-velocity runaway. Since MWC 349A is located in the direction of one of the most compact and massive associations in the Milky Way – the Cyg OB2 association (Knödlseider 2000), it is natural to assume that it is a member of this stellar system.

If MWC 349A is indeed a member of Cyg OB2, then the small angular separation between MWC 349A and MWC 349B might simply be due to a chance projection. The line of sight towards MWC 349A is nearly tangential to the local (Orion) spiral arm (whose extent in this direction is  $\sim 4$ – $6$  kpc; e.g. Russeil 2003), which makes the chance projection quite possible. The SIMBAD database<sup>5</sup> lists three O stars within 10 arcmin from MWC 349A, one of which, the O8 III (Negueruela et al. 2008) star 2MASS J20323843+4040445, is separated from MWC 349A by only  $\approx 1.8$  arcmin and is projected on the western edge of the  $24\ \mu\text{m}$  nebula (not far from the equatorial belt). We note, however, that recent very accurate parallax measurements

of five massive star-forming regions towards Cygnus X showed that four of them are located at a distance of  $1.4 \pm 0.1$  kpc (Rygl et al. 2012). At the same time, there are strong indications that most molecular clouds in Cygnus X form a coherent complex located at the same distance as Cyg OB2 (Schneider et al. 2006), which implies that Cyg OB2 is at the distance of  $1.4 \pm 0.1$  kpc as well (cf. Hanson 2003). From this it follows that the physical relationship between MWC 349A and MWC 349B and their membership of Cyg OB2 do not contradict each other, which in turn implies that MWC 349A should be as old as MWC 349B (i.e.  $\sim 5$  Myr). The obvious consequence of the latter implication is that MWC 349A cannot be a young stellar object, nor a post-AGB star.

To check whether the spectral classification of MWC 349B is consistent with the possibility that this star is a member of Cyg OB2, we used its visual magnitude and extinction of  $V = 14.3$  mag and  $A_V = 8.6$ – $8.9$  mag (Cohen et al. 1985), respectively, to derive the absolute visual magnitude  $M_V = -(5.0 \div 5.3)$  mag, which agrees well with that expected for a B0 III star.

Similarly, assuming the visual magnitude of MWC 349A of 14 mag (Cohen et al. 1985) and adopting  $A_V = 10.0$ – $10.6$  mag<sup>6</sup> (Cohen et al. 1985; Kelly et al. 1994), one has  $M_V = -(6.7 \div 7.3)$  mag. The absence of He II lines and the presence of strong He I emission lines in the spectrum of MWC 349A imply that the effective temperature of this star should be in a range from  $\sim 20\,000$  to  $28\,000$  K, which corresponds to a bolometric correction of  $-2.5 \pm 0.4$  mag (Hofmann et al. 2002). Thus, one derives a the stellar luminosity of  $\log(L/L_\odot) = (5.6 \div 5.9) \pm 0.2$  (cf. Hartmann et al. 1980; Hofmann et al. 2002). We caution that this luminosity estimate should be considered approximate because of the high ( $\approx 1$ – $2$  mag) photometric variability of MWC 349A: in the *B*-band its magnitude varies from  $\approx 14$  to 16 mag (Gottlieb & Liller 1978), while in the *R*-band it varies from  $\approx 9.5$  to 10.5 mag (Jorgenson et al. 2000). On the other hand, the good correlation between the brightness in the *V* and *R* bands in MWC 349A (see Fig. 1 in Yudin 1996) implies that  $V = 14$  mag corresponds to the minimum brightness of this star, so that its actual luminosity could be even higher.

The high luminosity of MWC 349A, along with its significant spectroscopic (e.g. Andrillat et al. 1996) and photometric variability, and the presence of the parsec-scale (bipolar) circumstellar nebula are typical of evolved massive stars belonging to the class of LBVs (e.g. Humphreys & Davidson 1994; Bohannan 1997). We therefore concur with Hofmann et al. (2002) that MWC 349A is an evolved massive star, likely an LBV (cf. Hartmann et al. 1980). This inference is supported by the possible existence of a high-velocity ( $\approx 260$  km s<sup>-1</sup>) component in the bipolar outflow (Tanaka et al. 1985), which might correspond to the LBV wind concentrated along the polar axis (we will return to this point in Sect. 3.3). Assuming that MWC 349A is an LBV of age of 5 Myr and using the above estimate of its luminosity, one can infer the zero-age main-sequence mass of this star of  $\sim 40 M_\odot$ .

### 3.2. MWC 349A as a runaway

MWC 349A is separated from the geometric centre of the Cyg OB2 association by  $\approx 24$  pc in projection. Cyg OB2 contains  $\sim 100$  O stars or stars with O-type progenitors and its half-light radius is  $\sim 6$  pc (Knödlseider 2000). The age of the association

<sup>4</sup> See Parker & Goodwin (2007), Selier, Heydari-Malayeri & Gouliermis (2011), and references therein for a different point of view.

<sup>5</sup> <http://simbad.u-strasbg.fr/simbad/>

<sup>6</sup> Note that the interstellar extinction towards the Cyg OB2 association is very patchy and ranges from  $\sim 5$  to 20 mag (Knödlseider 2000).

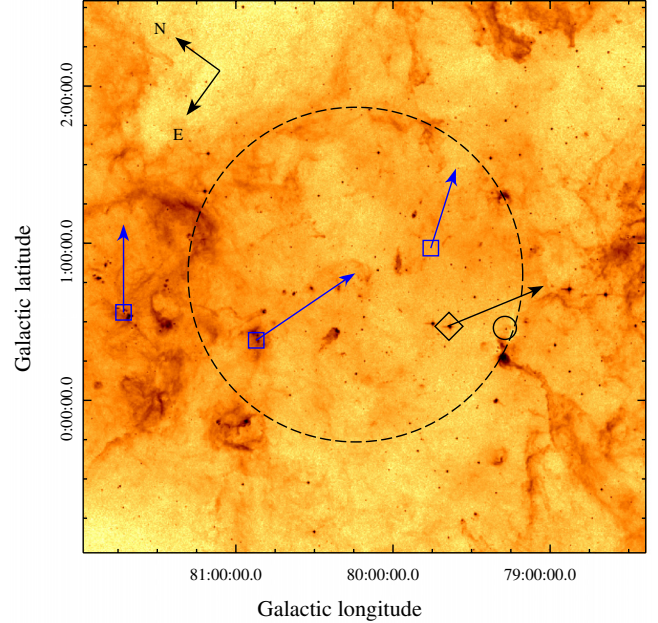
is  $\sim 5$  Myr (see Gvaramadze & Bomans 2008a, and references therein). Assuming that the association expands with a velocity equal to its velocity dispersion ( $\approx 2.4 \text{ km s}^{-1}$ ; Kiminki et al. 2007), one finds that the majority of massive stars in Cyg OB2 were originally concentrated in a region of radius of  $< 1$  pc. It is therefore plausible that several Myr ago the stellar number density in the core of Cyg OB2 was high enough to ensure that close dynamical encounters between its members were frequent, which is the necessary condition for the effective production of runaways. Currently only one runaway associated with Cyg OB2 is known – the O4 If star BD+43° 3654 (Comerón & Pasquali 2007; Gvaramadze & Bomans 2008a). Let us check whether MWC 349A might be another example of a massive star running away from Cyg OB2.

To check this possibility, we used the proper motion measurements for MWC 349A given in Rodríguez et al. (2007). To convert the observed proper motion ( $\mu_\alpha \cos \delta = -3.1 \pm 0.5 \text{ mas yr}^{-1}$  and  $\mu_\delta = -5.3 \pm 0.5 \text{ mas yr}^{-1}$ ) into the transverse peculiar velocity, we used the Galactic constants  $R_0 = 8.0 \text{ kpc}$  and  $\Theta_0 = 240 \text{ km s}^{-1}$  (Reid et al. 2009) and the solar peculiar motion  $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3) \text{ km s}^{-1}$  (Schönrich et al. 2010). The derived velocity components in Galactic coordinates are  $v_l = -7.3 \pm 6.8 \text{ km s}^{-1}$  and  $v_b = 3.0 \pm 3.3 \text{ km s}^{-1}$  (for the error calculation, only the errors of the proper motion measurements and the distance estimate were considered). With the transverse peculiar velocity of  $v_{tr} \approx 8 \text{ km s}^{-1}$ , MWC 349A would need  $\approx 3$  Myr to travel from the centre of the association to its current position.

Figure 3 shows that the peculiar velocity of MWC 349A has somewhat the “wrong” orientation, i.e. it does not point away from the centre of the Cyg OB2 association. To explain this misalignment, one can assume that Cyg OB2 has a peculiar (transverse) velocity of  $\sim 5\text{--}10 \text{ km s}^{-1}$  in the northwest direction (cf. Hoogerwerf et al. 2001). The peculiar velocity of just this magnitude and orientation is required to explain the relative position of the runaway star BD+43° 3654 and two young pulsars on the sky (Gvaramadze & Bomans 2008a). Peculiar velocities of  $\sim 10 \text{ km s}^{-1}$  are typical of the OB associations near the Sun (de Zeeuw et al. 1999). More importantly, three star-forming regions adjacent to the Cyg OB2 association (DR20, DR21 and IRAS 20290+4052) have peculiar (transverse) velocities of  $\approx 6\text{--}9 \text{ km s}^{-1}$  directed northwest and west (Rygl et al. 2012; see also Fig. 3).

To the peculiar transverse velocity of MWC 349A one should add the peculiar radial velocity,  $v_{rad}$ , which can be derived from the recession velocity of this star of  $8\text{--}12 \text{ km s}^{-1}$  (e.g. Thum et al. 1992; Gordon et al. 2001; Gordon 2003). After correction for differential Galactic rotation and solar peculiar motion, one has  $v_{rad} \approx 18\text{--}22 \text{ km s}^{-1}$  and the total space velocity  $v_{tot} \approx 20\text{--}23 \text{ km s}^{-1}$ . Although this velocity does not meet the usual criterion for defining runaway stars (i.e.  $v_{tot} > 30 \text{ km s}^{-1}$ ; Blaauw 1961), we note that the ejection of stars with low velocities is common (e.g. Gies 1987; Kroupa 1998; Gvaramadze & Bomans 2008b), so that any star unbound from the parent cluster should be considered as a runaway, independently of its peculiar velocity.

On the other hand, the derived total velocity of MWC 349A is too high to be consistent with the observed linear separation between MWC 349A and MWC 349B ( $\approx 3300 \text{ AU}$ ) and the possibility that these stars form a bound system. This inference follows from the results of numerical scattering experiments by Kroupa (1998), who showed that a wide binary system can survive the ejection process only if its space velocity is less than the orbital velocity. Simple estimates show that for any reasonable

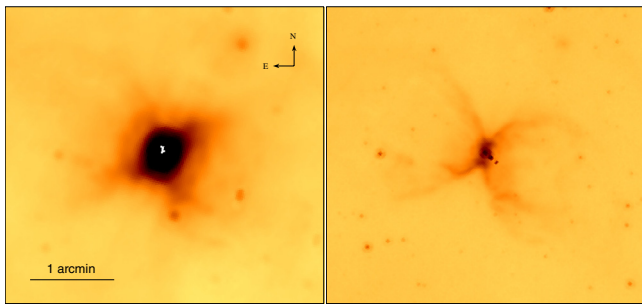


**Fig. 3.** *Midcourse Space Experiment (MSX)*  $8.3 \mu\text{m}$  image of the Cyg OB2 association and its environments. The approximate boundary of the association is shown by a dashed circle of a diameter of  $\approx 2^\circ$ . The position of MWC 349A is marked by a diamond, while that of the nearby cLBV GAL 079.29+00.46 is indicated by a circle. The arrows show the space motions of MWC 349A and three star-forming regions (indicated by squares). See text for details.

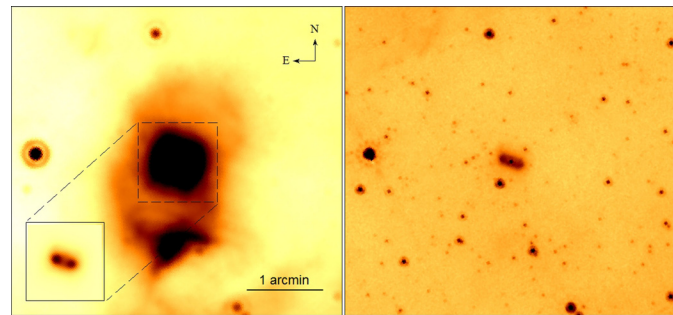
masses of MWC 349A and MWC 349B the orbital velocity of the binary is an order of magnitude lower than its space velocity. A single exception (i.e. a high-velocity wide binary) that occurred in the experiments by Kroupa (1998) was interpreted as the outcome of “a complex high-order interaction, that resulted in two stars being ejected on essentially identical trajectories”. Another possibility to produce a wide runaway binary is through the ejection of a compact, initially stable hierarchical triple system, which in the course of evolution of its components becomes unstable and dissolves into a binary star and a single unbound star. We discuss this possibility in Sect. 3.3 in more detail because it might be directly related to the formation of the bipolar nebula around MWC 349A.

To conclude, we note that MWC 349A is located at only  $\approx 20$  arcmin (or  $\approx 8 \text{ pc}$  in projection) from the cLBV GAL 079.29+00.46 (see Fig. 3). The distance estimates for GAL 079.29+00.46 (Voors et al. 2000) suggest that this star could be a member of Cyg OB2 as well. GAL 079.29+00.46 is surrounded by a curious circumstellar nebula consisting of two concentric circular shells (see, e.g., Fig. 2j in Gvaramadze et al. 2010a)<sup>7</sup>. The diameter of the inner (bright) shell is  $\approx 1.4 \text{ pc}$  (at the assumed distance to GAL 079.29+00.46 of  $1.4 \text{ kpc}$ ), while that of the outer shell is  $\approx 2.8 \text{ pc}$ . We speculate that the nebula around GAL 079.29+00.46 might actually have a bipolar geometry (similar to that around MWC 349A) with the polar axis parallel to our line of sight. In this case, the inner shell would correspond to the circular waist of the nebula around MWC 349A (whose diameter is  $\approx 1.1 \text{ pc}$ ), while the outer one to the bipolar lobes (whose diameter is  $\approx 2.4 \text{ pc}$ ). If subsequent studies of MWC 349A will prove its LBV nature, then along with GAL 079.29+00.46 it would represent one more

<sup>7</sup> For another example of a two-shell circumstellar nebula produced by the cLBV MN112 see Gvaramadze et al. (2010c).



**Fig. 4.** MIPS  $24\mu\text{m}$  (left) and IRAC  $8\mu\text{m}$  images of the bipolar nebula around the candidate LBV MN13 (Gvaramadze et al. 2010a). The orientation and the scale of the images are the same.



**Fig. 5.** MIPS  $24\mu\text{m}$  (left) and IRAC  $8\mu\text{m}$  images of the bipolar nebula around the blue supergiant MN18 (Gvaramadze et al. 2010a). The inset shows the waist of the nebula in a different intensity scale. The orientation and the scale of the images are the same.

example of massive stellar twinning (Walborn & Fitzpatrick 2000). Two other well-known examples of such twinning are the pairs of (c)LBVs: HD 168607 and HD 168625 (separated by only  $\approx 1.6$  arcmin) and AG Car and Hen 3-519 (separated by  $\approx 16.2$  arcmin).

### 3.3. Possible origin of the bipolar nebula around MWC 349A

In Sect. 3.1 we suggested that MWC 349A is likely an LBV star. Observations show that almost all LBVs are surrounded by compact nebulae with linear extent ranging from  $\sim 0.1$  to several pc (e.g. Weis 2001; Clark et al. 2005). These nebulae display a wide diversity of shapes, from circular to bipolar and triple-ring forms (e.g. Nota et al. 1995; Smith 2007; Gvaramadze et al. 2010a). As a rule, the youngest LBV nebulae have bipolar morphology<sup>8</sup> (see Table 1 in Weis 2011). Three well-known examples of young ( $\lesssim 10^4$  yr) bipolar nebulae associated with Galactic (c)LBVs are the Homunculus nebula of the LBV  $\eta$  Car (e.g. Morse et al. 1998), the two-lobe nebula around the cLBV Sher 25 (Brandner et al. 1997), and the triple-ring system around the cLBV HD 168625 (Smith 2007). Two other striking examples of hourglass-like nebulae produced by evolved massive stars were recently discovered with *Spitzer* (Gvaramadze et al. 2010a). One of them (Fig. 4) is created by the cLBV MN13 (Gvaramadze et al. 2010a; Wachter et al. 2011) and the second one (Fig. 5) by the blue supergiant star MN18 (Gvaramadze et al. 2010a). The MIPS  $24\mu\text{m}$  image of the nebula around MN13 shows that the brightest part of this nebula is reminiscent of the triple-ring system produced by the cLBV HD 168625 (see Fig. 1d in Smith 2007), while the IRAC  $8\mu\text{m}$  image shows that the waist of the nebula is surrounded by a belt similar to that of the  $24\mu\text{m}$  nebula around MWC 349A (the possible origin of such belts is discussed in Sect. 3.4). The MIPS and IRAC images of MN18 show that the central star is surrounded by a toroidal structure, which most likely is responsible for the pinching in the waist of the nebula.

The widely accepted explanation of the origin of two-lobe nebulae around evolved massive stars is that the (spherically symmetric) stellar wind is collimated by an aspherical (disk-like) circumstellar environment<sup>9</sup> (e.g. Frank et al. 1995; Langer et al. 1999). Such structures could form around single massive stars if they reach the  $\Omega$  limit (i.e. if the centrifugal force and the radiative acceleration cancel out gravity at the stellar

equator), so that the stellar wind becomes strongly confined to the equatorial plane (Langer 1997, 1998). Alternatively, the origin of disk-like density enhancements could be caused by various binary interaction processes, such as (i) common envelope ejection (e.g. Morris 1981), (ii) mass loss through the second Lagrange point  $L_2$  (e.g. Livio et al. 1979), and (iii) focusing of the primary's wind towards the orbital plane by the gravitational field of the companion star (e.g. Fabian & Hansen 1979; Mastrodemos & Morris 1999). All of these processes can produce outflowing (excretion) disks in the orbital plane.

In Sect. 3.2 we mentioned that the large linear separation between MWC 349A and MWC 349B could be reconciled with their physical relationship if both stars were originally members of a hierarchical triple system. In support of this possibility we note that Jorgenson et al. (2000) reported detection of a nine-year periodicity in the red-light variations of MWC 349A, which implies that the star itself might be a binary system (Jorgenson et al. 2000; Hofmann et al. 2002). Below we show how an initially stable runaway triple system could be dissolved into a binary system and a single unbound star, and suggest that the gravitational focusing of the slow wind emanating from MWC 349A during the red supergiant phase might be responsible for the origin of disk-like circumstellar environment, which in turn is responsible for the origin and shaping of the observed bipolar nebula.

Imagine that the inner binary of the triple system was composed of MWC 349A (with the zero-age main-sequence mass,  $m_1$ , of  $40 M_{\odot}$ ) and a low-mass star (with the mass,  $m_2$ , of, say,  $5 M_{\odot}$ ), while MWC 349B (with the mass  $m_3 = 20 M_{\odot}$ ) was in a wide orbit. For the sake of simplicity, we assume that initially both orbits were circular. This triple system would be hard enough to survive dynamical ejection from Cyg OB2 if the orbital separation of the outer binary  $a_{\text{out}} \lesssim 100$  AU, while the system itself would be stable if the ratio of the outer to inner orbital periods  $X \equiv P_{\text{out}}/P_{\text{in}} \gtrsim 4$  (Kiseleva et al. 1994), i.e. if the orbital separation of the inner binary  $a_{\text{in}} < 35$  AU. A star with initial mass of  $40 M_{\odot}$  evolves through the red supergiant and yellow hypergiant phases (e.g. Humphreys 1991; Oudmaijer et al. 2009) and at the beginning of the LBV phase has a mass of  $\approx 20 M_{\odot}$ . Adopting this mass as the current mass of MWC 349A, one has the current mass of the inner binary of  $25 M_{\odot}$ , so that the nine-year orbital period of this binary corresponds to an orbital separation of  $\approx 13$  AU (i.e. the secondary star orbit within the disk; cf. Jorgenson et al. 2000). The large orbital separation implies that the inner binary did not experience the common envelope phase, i.e. the mass decrease of the primary star (MWC 349A) caused by (spherically symmetric) stellar wind mass loss led only to the

<sup>8</sup> Note that these nebulae may become more spherical with time because of the lateral expansion of their polar lobes (cf. Sect. 3.4).

<sup>9</sup> Another possibility is that the stellar wind is intrinsically bipolar (Owocki & Gayley 1997; Maeder & Desjacques 2001).

increase of the orbital period and separation of the binary by factors of  $(45/25)^2$  and  $45/25$ , respectively. Thus, the initial orbital period and separation of the inner binary were  $\approx 3$  yr and  $\approx 8$  AU, respectively.

Let us assume that initially the triple was stable (i.e.  $X > 4$ ). In the process of ejection from Cyg OB2 the outer binary acquired an eccentricity  $e_{\text{out}}$  (cf. Hoffer 1983; Hills 1975) and the perturbed triple system remained stable provided that

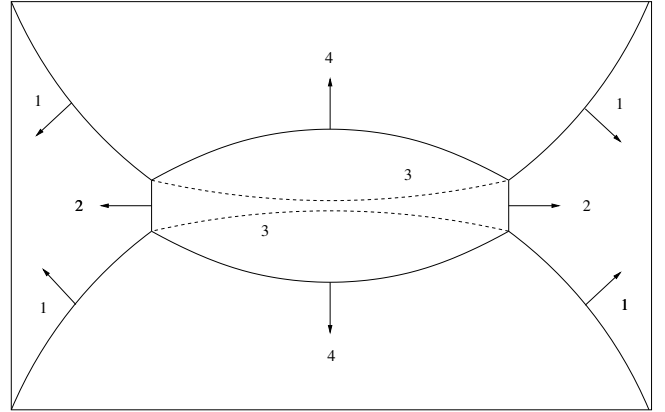
$$e_{\text{out}} \lesssim 1 - \frac{F(x)}{X^{2/3}}, \quad (1)$$

where

$$F(x) = \frac{2.4x^2 + 1.1x + 3.7}{(1+x^3)^{1/3}(1+x)} \quad (2)$$

and  $x = [(m_1 + m_2)/m_3]^{1/3}$  (Eggleton & Kiseleva 1995; Livio & Pringle 1998). Assuming  $X = 10$  (i.e.  $P_{\text{out}} = 30$  yr and  $a_{\text{out}} \approx 40$  AU), one finds from Eqs. (1) and (2) that the system is stable if  $e_{\text{out}} \lesssim 0.42$ . We assume that  $e_{\text{out}}$  obeys this condition (say,  $e_{\text{out}} = 0.30$ ), so that the triple remains intact until the primary of the inner binary, MWC 349A, evolved off the main sequence and lost half of its initial mass during the red supergiant and yellow hypergiant phases. In response to the mass loss the orbital periods of the outer and the inner binaries increased by factors of  $(65/45)^2 = 2.09$  and  $(45/25)^2 = 3.24$  (we assume that  $m_2$  and  $m_3$  are constant), so that  $X$  decreased by a factor of 0.64 and the condition for stability of the triple becomes  $e_{\text{out}} \lesssim 0.19$ . The spherically symmetric mass loss does not affect the eccentricity of the (inner and outer) binaries (e.g. Eggleton 2005). This and our assumption of  $e_{\text{out}} = 0.30$  implies that reduction of the mass of MWC 349A made the system unstable. According to the numerical experiments by Kiseleva et al. (1994), an unstable triple dissolves within  $\sim 100$  crossing times (which in our case corresponds to  $\sim 10^4$  yr) and leaves behind a binary system and a single unbound star. Thus, we propose that this binary system corresponds to MWC 349A and its putative low-mass companion, while MWC 349B is the third component of the triple, which became unbound in the recent past.

We speculate that the slow (red supergiant) wind from MWC 349A was focused by the gravitational field of the companion star to produce a circumbinary disk (see, e.g., Mastrodemos & Morris 1999), which allows the current fast (LBV) wind of MWC 349A to expand only in the polar directions and is responsible for the B[e] morphology of the stellar spectrum. We speculate also that the hourglass-shaped low-velocity outflow observed as the subarcsecond radio nebula originates because of gas entrainment in the boundary layer between the stellar wind and the disk, while the wind itself is confined near the polar axis of the slow outflow and is mostly unobservable. The possible existence of a high-velocity ( $\approx 260$  km s $^{-1}$ ) component in the bipolar radio nebula (Tanaka et al. 1985) conforms with our scenario and could be attributed to the stellar wind channelled along the polar axis. The energy injected into the ambient medium by the stellar wind leads to the origin of parsec-scale laterally expanding lobes, which we observe as the mid-infrared hourglass nebula. For a wind velocity of 260 km s $^{-1}$  and a linear extent of the lobes of  $\approx 3$  pc, one derives a kinematic age of the nebula of  $\approx 10^4$  yr. Note that this timescale is comparable to the dissolution time of the triple system (see above), so that it is likely that MWC 349B became unbound from MWC 349A only recently. This explains why these stars are still close to each other.



**Fig. 6.** Schematic of the proposed origin of the belt around the waist of the  $24 \mu\text{m}$  bipolar nebula associated with MWC 349A (not to scale): (1) the incident hemispherical shock wave (one of the two lobes of the nebula); (2) the ring-like Mach shock wave (the belt); (3) the tangential discontinuity; (4) the reflected shock wave. See text for details.

### 3.4. Origin of the equatorial belt of the parsec-scale nebula

Now we discuss the possible origin of the belt around the waist of the mid-infrared nebula associated with MWC 349A (cf. Gvaramadze 1998). Near the waist each lobe of the bipolar nebula can be considered as a hemispherical shock wave, which collide with each other in equatorial plane (see Fig. 6 for schematic of this interaction). During the collision, the equatorial plane acts as a wall from which the incident waves are reflected. Initially, the reflection occurs in a regular fashion: the incident and reflected shock waves touch the “wall”. However, when the angle between the wall and the tangent to the incident shock becomes greater than some critical value ( $\phi_{\text{cr}} \approx 35^\circ$  for a medium with an adiabatic index of 5/3), the regular reflection becomes impossible (e.g. Courant & Friedrichs 1948). The incident shock wave is reflected without reaching the equatorial plane. In addition to the incident and reflected shock waves, another shock wave appears, which propagates parallel to the wall (Fig. 6). Such a reflection is called a Mach reflection, and the emerging new shock wave (in our case, in the shape of a belt; cf. Chernin et al. 1995) is called the Mach shock wave. The three shock waves intersect along a single (circular) line, from which the surface of a tangential discontinuity separates the medium behind the Mach shock wave from the medium that passes through the incident and reflected ones.

The velocity of the Mach shock wave  $v_M$  is related to the velocity of the incident shock wave  $v_i$  by  $v_M = v_i/\sin \phi$ , where  $\phi$  is the angle between the tangent to the front of the incident shock and the equatorial plane of the nebula. The Mach wave reaches its maximum velocity at the beginning of the Mach reflection, i.e., at  $\phi = \phi_{\text{cr}}$ :  $v_M^{\text{max}} \approx 1.7v_i$ . As the angle  $\phi$  increases further,  $v_M$  decreases, and the Mach wave degenerates. Using the  $24 \mu\text{m}$  image of the nebula, we estimated that  $\phi \approx 50^\circ$ , so that we expect that the belt expands with a velocity of  $\approx 1.3$  times exceeding the local lateral expansion velocity of the bipolar lobes.

Our interpretation of the belt around the waist as a Mach shock is testable. In Sect. 2.3 we mentioned that the waist has an optical counterpart and that its western edge coincides with a prominent H $\alpha$  filament (Marston & McCollum 2008). If the belt is indeed the Mach shock, we expect that high-resolution spectroscopy of the H $\alpha$  nebula would show that the expansion velocity of the belt is higher than that of the adjacent parts of the lobes.

## 4. Summary

We have reported the discovery of a parsec-scale bipolar nebula around the curious emission-line star MWC 349A. The morphology of the nebula and its orientation are similar to those of the well-known (~400 times smaller) radio nebula associated with MWC 349A. The close similarity of the two nebulae suggests that they are shaped by the same agent – the disk around MWC 349A. Significant photometric and spectroscopic variability of MWC 349A along with the presence of the parsec-scale bipolar nebula strongly argue that this star is an LBV. We have discussed the physical relationship between MWC 349A and the nearby B0 III star MWC 349B and suggested that both stars were members of a hierarchical triple system, which was dynamically ejected from the core of the Cyg OB2 association several Myr ago. The stellar wind mass loss from the most massive (~40  $M_{\odot}$ ) star in the triple (MWC 349A) made the system unstable, so that it dissolved into a binary (MWC 349A) and a single unbound star (MWC 349B). The binary nature of MWC 349A is supported by the existence of a nine-year periodicity in the red-light variations of this star. We proposed that the gravitational focusing of the slow (red supergiant) wind from MWC 349A by the companion star led to the origin of a circumbinary disk, which currently collimates the fast (LBV) wind of MWC 349A and is responsible for the B[e] morphology of the stellar spectrum.

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