The colliding winds of WR 146: seeing the works

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Abstract: WR146 is a WC6+O8 colliding-wind binary (CWB) system with thermal emission from the stellar winds of the two stars, and bright non-thermal emission from the wind-collision region (WCR) where the winds collide. We present high resolution radio observations from 1.4 to 43 GHz that give one of the best quality radio spectra of any CWB to date. Observations at 22 GHz now span 8 years, and reveal the proper motion of the system, allowing comparison of multi-epoch data. VLBI observations show the location of the WCR relative to the stellar components, from which the wind momentum ratio can be shown to be $\eta = 0.06 \pm 0.15$. The radio spectrum and the spatial distribution of emission are modelled, and we determine the contribution of both stellar winds and the WCR to the observed emission. We show that our current models fail to account for the high frequency spectrum of WR146, and also produce too much emission far from the stagnation point of the wind collision.

1 Observations

On 2004 October 1, WR 146 was observed at 1.4, 4.8, 8.3, 15, and 43 GHz with the highest-resolution configuration of the Very Large Array (VLA) in conjunction with the Pie Town antenna of the Very Large Baseline Array (VLBA). Two components are observed at 15, 22, and 43 GHz. At 43 GHz, the two sources are separated by 152 ± 2 mas (Fig. 1 - left). The northern component (N) has a predominately synchrotron spectrum at almost all frequencies, except at 43 GHz where it is a combination of emission from the WCR and the O star stellar wind (see Fig. 3). The southern source (S) has a thermal spectrum and we identify this as the wind from the WC6 star (Dougherty et al. 1996, 2000), which STIS spectroscopy confirms is the spectral type of the southern component.

WR146 was also observed at 4.9 GHz using the European VLBI Network (EVN) and the MERLIN array in the UK on 2001 February 12. The EVN observation shows a bow-shaped arc of emission (Fig. 1 - centre), with a brightness temperature of 10^7 K, which we identify as the WCR. Such a shape is consistent with the WCR "wrapping" around the star with the lower wind momentum, the northern O star (e.g. see Eichler & Usov 1993, Dougherty et al. 2003). The EVN observations indicate the WR and O star are south and north of the WCR, consistent

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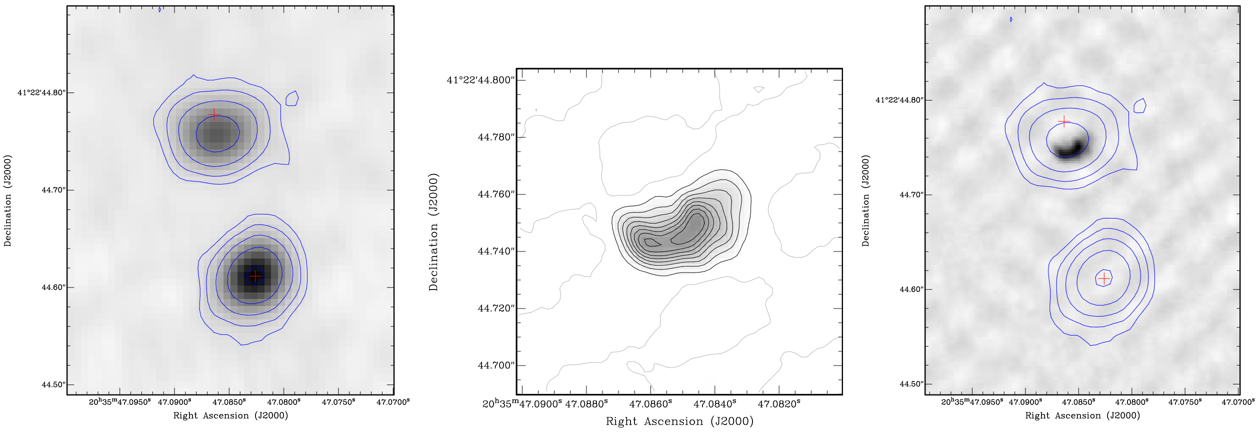

Figure 1: (Left) WR146 with VLA+PT at 43 GHz, with resolution of 30 mas. Two sources are clearly observed, with a separation of 152 ± 2 mas. (Centre) EVN observation at 5 GHz with resolution of 9 mas. A bow-shaped region is observed as expected for a WCR. (Right) An overlay of the VLA 43 GHz (contours) with the EVN (greyscale) 5-GHz emission shown. The proper motion of the source between the observations has been taken into account. The stellar positions are marked, as deduced from HST observations, with a separation of 168 mas.

with previous suggestions (Dougherty et al. 1996, 2000; Lépine et al. 2001). MERLIN also detects only the WCR.

2 Proper motion

In order to align correctly radio images of any stellar source obtained at widely separated epochs it is necessary to know the proper motion of the source. In addition to the VLA observations from 2004, WR 146 was also observed at 22 GHz with the VLA on 1996 October 26 and 1999 August 26. Each of these observations was phase-referenced using the same quasar, J2007+404, and the change in the relative position of WR 146 and J2007+404 can be determined over the 8 years of observations. A weighted regression fit to the relative positions of WR146 leads to a proper motion of $\mu_\alpha = -3.65 \pm 0.17$ and $\mu_\delta = -6.46 \pm 0.40$ mas yr^{-1}.

3 Component separation and wind-momentum ratio

By observing the relative position of the stars and the WCR (located around the stagnation point of the two stellar winds), we can determine the wind-momentum ratio η. After taking account of the proper motion, a comparison of the EVN and VLA observations reveal the position of the WCR relative to the WR star, with a separation of 135 ± 6 mas. From Niemela et al. (1998), the HST observed a separation of 168 ± 31 mas between the WR and O stars. Taking the uncertainty of the location of the stagnation point as the half-width of the WCR as detected by the EVN, we find $\eta = 0.06 \pm 0.15$. The bulk of the error is due to the uncertainty of the stellar separation (± 31 mas).

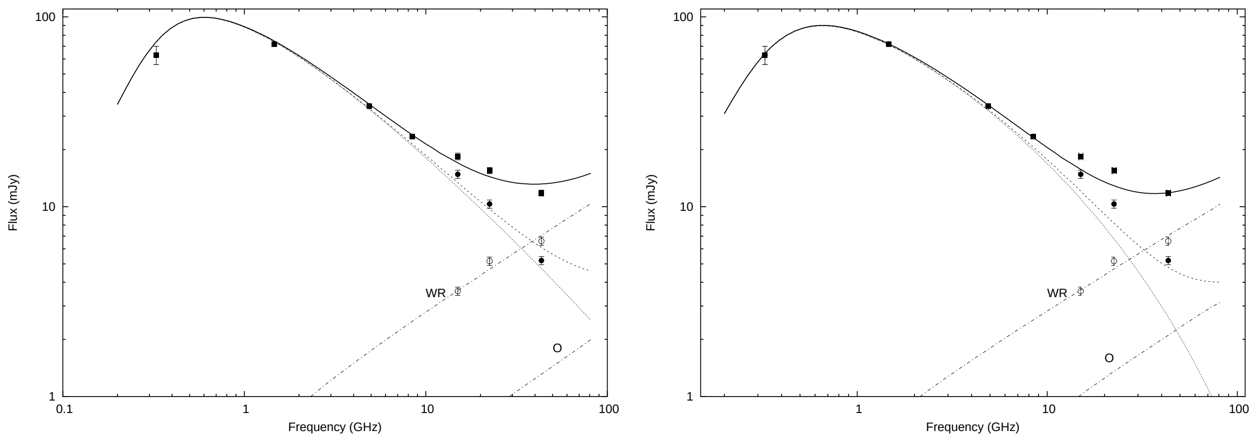

Figure 2: Comparison of observations and two model spectra of WR146. Solid squares mark the total flux from N+S (327 MHz datum from Taylor et al. (1996)), solid circles the flux from N and open circles that from S. Best-fit models of the emission from component N (synchrotron - dotted; thermal - lower dot-dashed; synchrotron+thermal - dashed) and the thermal emission from S (higher dot-dashed) are shown. The total flux from N+S is shown by the solid line. The two models presented are where the high frequency synchrotron spectrum is determined by IC cooling (left) or the high energy cutoff of the shock accelerated electrons (right).

4 Modelling the spectrum

We have modelled the radio emission from WR 146 using a hydro-dynamical model of the density and pressure distribution of a colliding-wind system and solving the radiative transfer equation for thermal and magneto-bremsstrahlung emission and absorption, as well accounting for the Razin effect, inverse-Compton (IC) and Coulomb cooling (Dougherty et al. 2003, Pittard et al. 2005). The model successfully recovers the total flux up to 8.3 GHz. At higher frequencies the fit is less convincing, due to a poor model of component N. Either the 43-GHz flux is overestimated or the 15 and 22-GHz fluxes are underestimated (see Fig. 2). These problems can be resolved if the synchrotron spectrum steepens around ~ 22 GHz.

5 Simulated observations

Using the model parameters derived from the spectrum we can generate synthetic images of WR146, using the AIPS routine UVCON. This allows us to “observe” our model (Fig. 3), and impose constraints on the model from the spatial distribution of the model emission. The similarities between the synthetic images and the observations is remarkable, particularly at 43 GHz. Clearly, the 43-GHz emission is a combination of O-star stellar wind and WCR emission - its peak is not located at either the contact discontinuity or the stellar position, but between them. Comparison with Fig. 1 (left) suggests the emission from N is too extended, both E-W and N-S. The EVN model image also reveals the spatial distribution of the model emission is too wide. We conclude that the model produces too much emission far from the stagnation point of the WCR. Our models also show that deducing the location of the stagnation point from observations is complicated by the relative brightness of the WR and O-star shocked plasma in the WCR.

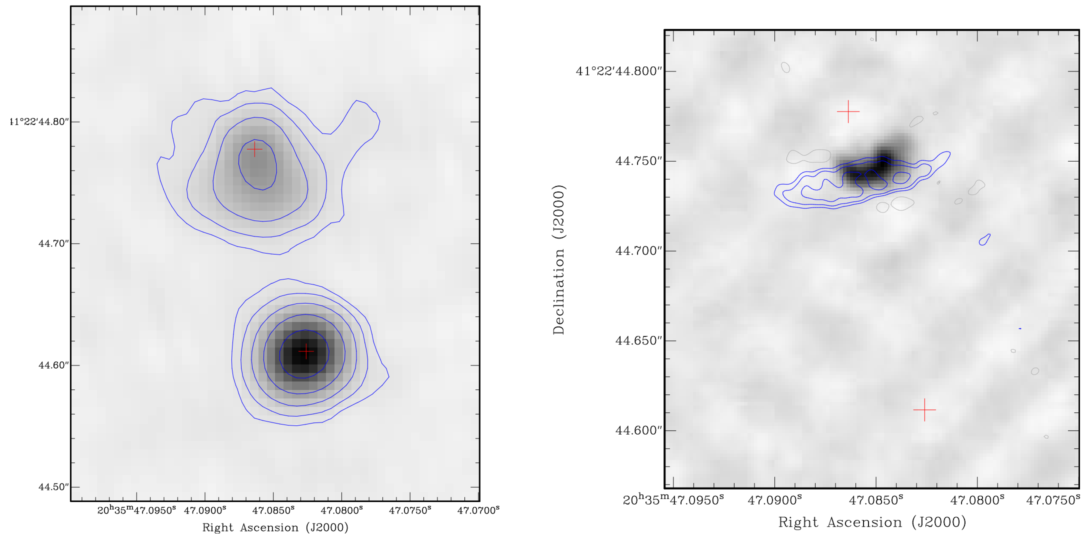

Figure 3: Simulated observations of WR146 at 43 GHz with the VLA+PT (left), and at 4.9 GHz with the EVN (right). The input 43-GHz model is based on the model from Fig. 2 (right), and the EVN model from Fig. 2 (left). The crosses mark the relative location of the two stars as determined by HST observations . Compare the left-hand figure to Fig. 1 (left). The EVN observation and simulated data are superimposed for a clear comparison.

Acknowledgments

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