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The Equatorial Outflow of SS 433

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Abstract. We present VLBI imaging results for SS 433 from the period 1995–2000. An equatorial emission region is detected and confirmed in 7 experiments at 1.6 and 5 GHz. The structure of the region changes with time on scales of weeks to months. The nature of emission is unknown, but it is certainly non-thermal, maybe optically thin synchrotron. The spectrum however might be attenuated by a thermal population of electrons. There were previous indications for an equatorial outflow from the system. We do detect outward motion of a radio component, and estimate a speed of 1200/sin(i) km/s. Theoretical work and IR observations suggest that the mass-loss rate in SS 433 is much higher in this region than in the jets. We suggest that the high-mass microquasars might all have equatorial outflows; in fact, it is the dominant form of mass-loss in these systems.

1. Introduction

Microquasars are Galactic X-ray binary systems harboring a compact object (neutron star or black hole). They produce well collimated, relativistic jets in which energetic electrons are radiating via the synchrotron process. SS 433 is the brightest permanent radio source of this class. Its precessing jets were first identified from the Doppler-shifted optical "moving" lines (Margon & Anderson 1989), and subsequently imaged by MERLIN, VLA, and the EVN. In the 90s VLBI arrays became more sensitive, and their resolution and imaging fidelity improved significantly. This enabled us to study the SS 433 radio beams at a level of unprecedented details.

The results presented here were observed in nine experiments, listed in Table 1. The paper briefly summarizes this work, focusing on the equatorial emission region, that is related to an outflow perpendicular to the well studied jets (Paragi et al. 1998,1999).

Table 1. List of VLBI experiments

Date of obs.	VLBI Array	Freq. [GHz]
6 May 1995	VLBA+Y1[a]	1.6, 5, 15
26 March 1998	VLBA+Y1	5, 8.4, 15, 22
18 April 1998	VLBA+Y1	5, 8.4, 15, 22
22 May 1998	VLBA+Y1	5, 8.4, 15, 22
6 June 1998	EVN+MERLIN +VLBA+Y1	1.6
16 June 1998	VLBA+Y1	5, 8.4, 15, 22
13 Feb. 2000	EVN+HartRAO+VLBA	1.6
20 Feb. 2000	EVN+HartRAO+VLBA	1.6
27 May 2000	EVN+HartRAO+VLBA	1.6

[a] a single element of the VLA

2. The Equatorial Emission Region

The SS 433 jets have been studied for two decades. Their kinematic model is very well established by optical and radio observations. However our data from 1995 observations showed two emission regions quasi-perpendicular to the beams. The emission was clearly identified at 1.6 GHz, and even at 5 GHz (apparent when convolving with the beam of the L-band image or larger). The spectral index of the emission was remarkably steep ($\alpha \sim -1$). The follow-up global VLBI experiment in 1998 fully confirmed the existence of equatorial radio components with a similar disposition, but at a different distance from the center and at a slightly different position angle (see Fig. 1). The emission spans about 100 mas, corresponding to several hundreds of Astronomical Units (1 mas=5 AU at a distance of 5 kpc). A brightness temperature of $10^7 - 10^8$ K is determined that is indicative of non-thermal emission (Paragi et al. 2001a, 2001b).

3. Indications for outflow

Observations in other wavebands indicated the presence of an equatorial outflow in the system. Zwitter et al. (1991) invoked a disk-like outflow to explain the asymmetric optical light curve, while Kotani et al. (1996) suggested a sprinkling disk in order to explain the X-ray line ratios of Fe XXV Kα red- and blue-shifted lines. At the same time Chakrabarti and Matsuda (1992) showed by numerical simulations that a significant fraction of the accreted matter in SS 433 may leave the system through the L_2 Lagrangian point (for more details see Paragi et al. 1999, and references therein).

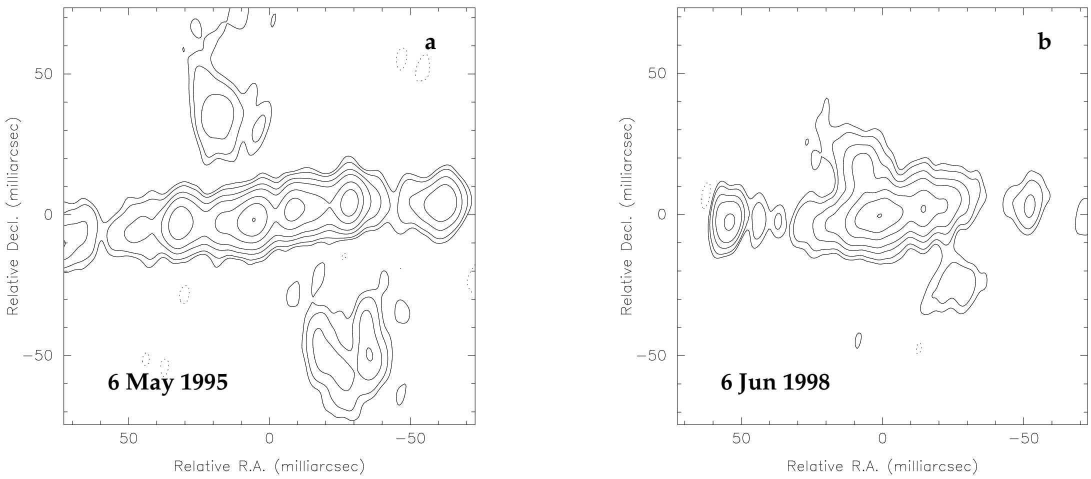

Fig. 1. The equatorial emission region in 1995 (**a**) and 1998 (**b**) at 1.6 GHz. There are changes in the position angle and the separation of the components, but the overall structure is similar. The contour levels are at ±1, 2, 5, 10, 25, 50, 99%. The peak flux densities and the restoring beams are **a** 53.6 mJy/beam; 11.1×5.6 mas at $PA = -4$ deg, and **b** 38.7 mJy/beam; 10.8×3.8 mas at $PA = -5.7$

Recent work by King et al. (2000) indicates that SS 433 can only avoid a common envelope evolutionary phase (i.e. no binary system, no jets) if most of the accreted matter is expelled by a high radiation pressure. This scenario invokes a massive equatorial outflow with a mass-loss rate of about 10^{-4} $M_\odot$/yr. Apart from the direct detection in the radio regime (Paragi et al. 1999), there is other recent observational evidence supporting this idea. Gies et al. (2001) studied the UV spectrum with the Hubble Space Telescope. They detect Hα and He I stationary emission lines, sometimes showing P-Cygni profile. These lines originate in an expanding thick disk, embedding the central binary system. Fuchs et al. (in press) analyzed IR spectra of the source. They also invoke an expanding disk-wind scenario, and fit a 150 K free-free component to the spectrum (the IR emission certainly comes from a larger volume than the UV line emission). The estimated outflow rate is in the order of 10^{-4} $M_\odot$/yr. These results draw our attention to the fact that the mass-loss rate is about 100 times larger than what we observe in the radio beams!

4. Direct detection of the outflow?

In 1998 at two epochs of our multi-frequency VLBA monitoring of SS 433, we identified component N1 at 5 GHz (Fig. 2), at 1.6 GHz detected as a bright region North to the center (see Fig. 1b). Our higher resolution at 5 GHz enables us to trace the apparent motion of N1 from the central region. We estimate a motion of 1200/sin(i) km/s, where i is the inclination of the velocity vector of N1 to the line of sight. Although this speed is fairly consistent with an early type stellar wind, and similar speeds have been reported in SS 433 (Panferov & Fabrika 1997), we are not yet fully convinced that this structural change really represents bulk motion of the outflow. Note that we could not find high velocity H I gas in the system with the Westerbork Synthesis Telescope. Note that on Fig 2b a new component (N2) appeared at a different position angle.

Observations in 2000 do not allow an accurate proper motion estimate, but clearly confirm outward motion from the center (Fig. 3). At the first two epochs we see roughly the same structure — much smoother emission than in previous experiments. At the third epoch a new component appears, very close to the center. So new components always show up close to the central region. It seems that the appearance of these features is related to the precessional cycle, and they move away from the central engine on a timescale of weeks/months.

5. Nature of emission

Blundell et al. (2001) recently confirmed the existence of the equatorial emission. They have observed a smooth structure with a global VLBI array of VLBA, MERLIN, and the phased VLA at 1.6 and 5 GHz. The spectral index of the region at the epoch of observation was flat. As we have shown above, the appearance of the emission is changing with time: sometimes it is blob-like, another time it is smoother. An interesting new result of their experiment is that the spectral index also changes. Blundell et al. explain the flat spectral index with thermal free-free emission. Because there is no other observational support for this idea (e.g. X-rays coming from the region), and because it is difficult to explain how the ISM could be heated up to $10^7 - 10^8$ K on hundreds of AU scales, we consider this scenario to be unlikely. In fact there are observations that directly contradict to this model, to mention only one, the observed steep spectral index in 1995.

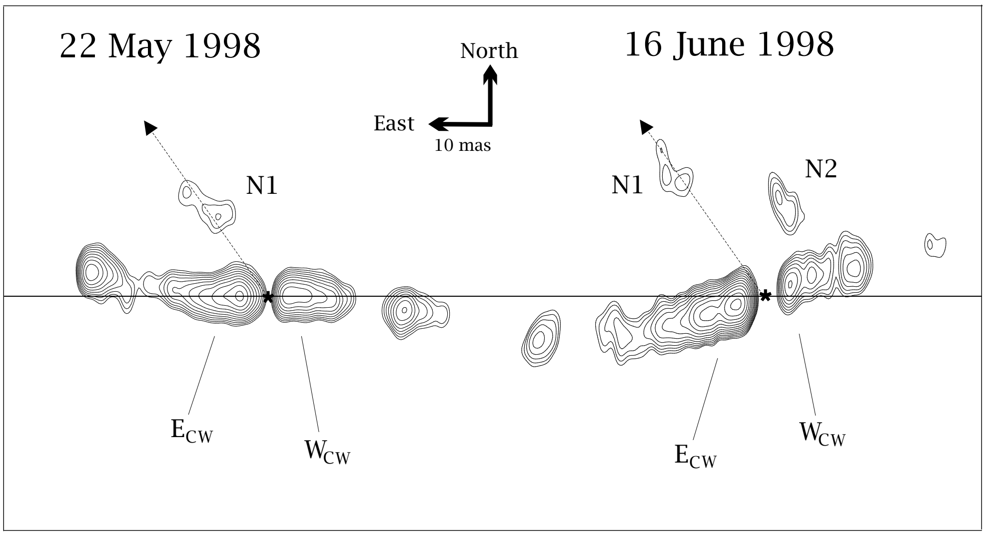

Fig. 2. VLBA maps of SS 433 at 5 GHz in 1998. The central engine – indicated by an asterisk – is located in between the Eastern and Western core-wings (E_{cw} & W_{cw}, these correspond to the approaching and the receding jet sides at the epochs of observations, respectively). N1 is moving away from the center with a projected speed of ∼1200 km/s. Note that this component is the the same as the bright Northern equatorial feature in Fig. 1b (from Paragi 2001)

There is a possibility that in fact we observe synchrotron radiation. Even the flat spectral index can be reconciled with this interpretation, if there is a mixed population of relativistic and thermal electrons (see White (1985) for details). The question is now how and where these energetic electrons are produced. Whether these particles are accelerated in shocks in the ISM or most of them originate from the vicinity of the central engine is an open question, but the latter seems to be more plausible.

6. Conclusions

We detect the equatorial outflow of SS 433 that have already been envisaged by other groups based on optical and X-ray observations, and numerical simulations of the system. The outflow speed is estimated to be $1200/\sin(i)$ km/s, but this result has not been confirmed yet.

Because there are indications for equatorial outflows in other systems as well, moreover theoretical work and numerical simulations suggest that there is a significant mass-loss in high-mass X-ray binary systems, we conclude that equatorial outflows might be common in microquasars harboring a massive normal star. In fact, the mass-loss rate could be much higher in these outflows than in the radio jets, as demonstrated for SS 433.

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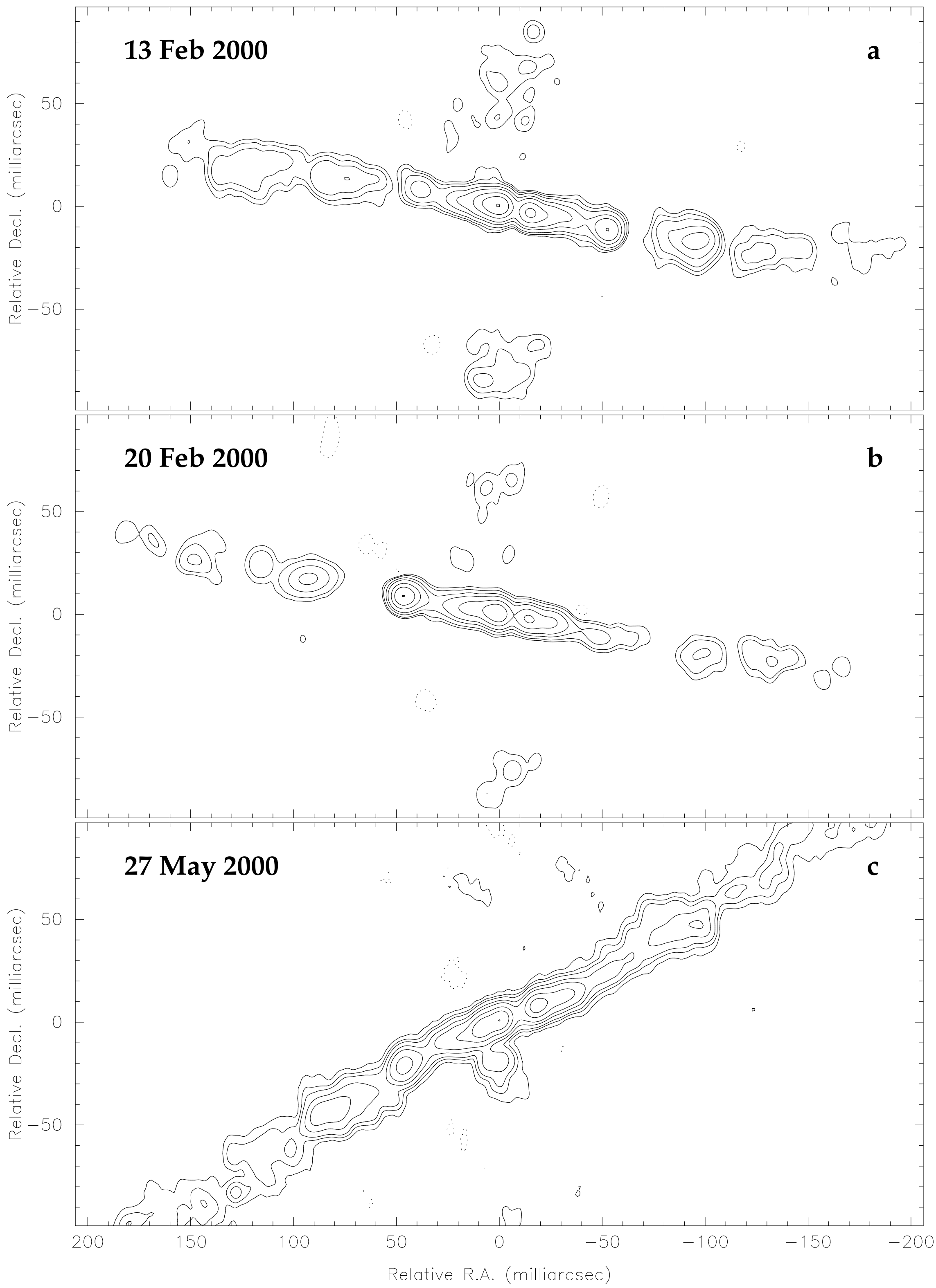

Fig. 3. Global VLBI images of SS 433 at 1.6 GHz on **a** 13 Feb 2000, **b** 20 Feb 2000, and **c** 27 May 2000. The equatorial emission region (to the N and S) is similar at the first two epochs. Note that the Northern and Southern emission features are not symmetrical to the brightest component, but to the central engine, located in between the Eastern and Western jets. At the third epoch there is a new "component" emerging from the central region. At the full resolution image it is well separated from the jet (thanks to Hartebeesthoek). The images were restored with a 8×6 mas beam with $PA = 0$ deg. The contour levels are ±1, 2, 5, 10, 25, 50, 99% of the peak flux densities of **a** 35.9 mJy/beam (lowest contours are ±0.5), **b** 27.4 mJy/beam, and **c** 34.1 mJy/beam (lowest contours are ±0.3)