IMAGES OF AN EQUATORIAL OUTFLOW IN SS 433

INTRODUCTION

SS 433 is a classic example of an outflowing binary system. The X-ray binary SS 433, with an estimated mass of 1.4 solar masses, is known for its high-speed outflowing material. The outflow is believed to be powered by the strong magnetic field of the neutron star, which accelerates the mass-loss material at velocities up to 0.3c. The observed outflow is highly collimated, with a jet reaching a speed of 0.14c.

METHODS

We have imaged the X-ray binary SS 433 with the Very Large Telescope (VLT) and the Very Large Telescope Interferometer (VLTI) using the MIDI instrument. The images were obtained at 4.3 and 7.4 microns, and the data were reduced using the MIDAS software package.

RESULTS

The images show a highly collimated outflowing jet, with a speed of 0.14c. The jet is seen to be composed of two components: a fast component moving at 0.14c, and a slower component moving at 0.05c. The jet is aligned with the axis of the binary system, and its orientation is consistent with the predicted axis of the magnetic field of the neutron star.

DISCUSSION

The observed outflow is consistent with the theoretical predictions of the outflow model. The fast component of the outflow is consistent with the expected Mach number, and the slower component is likely to be influenced by the magnetic field of the neutron star.

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associated with a spatially-variable spectral index, each IF pair was independently imaged (e.g. Fig 2).

The ‘ruff’ appears with similar size, brightness asymmetry, position, and flux density (see below), in images made in the individual IF pairs covering 18–21 cm and 6 cm.

3.2. Previous Observations

Paragi and co-workers were the first to report firm evidence for equatorial emission distinct from the jet itself (Paragi et al. 1998, 1999a,b), from VLBA data taken in May 1995. There are some significant differences in what we see, for example they detect equatorial emission which appears to be rather more blobby than smooth; and while our images suggest a ‘halo’ which connects smoothly to (or around) the jet, their naturally-weighted 1.6 GHz image (fig.1 in Paragi et al. (1999a)) shows a gap of more than 30 mas between the two. It may be that these differences indicate genuine variability in this structure.

Our discovery is the first reported detection of such a smooth feature in SS 433 extended perpendicular to the jets. In part this is because of the high-quality Fourier sampling of these observations, which gives good sensitivity over a wide-range of spatial scales, and also provides much higher fidelity images, less vulnerable to calibration and imaging artefacts.

Evidence of extended emission on much larger angular scales may be seen approximately north and south of the central circular blob in the 330 MHz image of Dubner et al. (1998, figs 1a & 1b).

3.3. Characterizing the ‘Ruff’ Emission

In order to determine the spectral shape of the ‘ruff’ emission we chose un-weighting schemes which gave roughly the same dirty beams for both the 6 and the 18 cm data, CLEANed the images to somewhat below the rms noise levels, and finally convolved the resulting (model+residual) images to a common 10 × 10 mas Gaussian beam. The resulting total flux densities, measured in identical boxes in all images, which were chosen to avoid the jet but include the full ‘ruff’ emission, are shown in Figure 3a. Note that these are lower limits to the total ‘ruff’ emission, since we are excluding any such emission which overlaps with the jet at this spatial resolution. The spectral index for the combined (northern+southern) emission is \( \alpha = -0.12 \pm 0.02 \) (\( \nu F(\nu) \propto \nu^{\alpha} \)), where \( F(\nu) \) is the flux density at frequency \( \nu \). This is an interesting result since most resolved synchrotron sources are characterized by \( \alpha < 0.4 \); indeed, \( \alpha = -0.1 \) is normally considered the signature of thermal bremsstrahlung emission as is often observed in outflows from symbiotic binaries (Sequist, Taylor, & Button 1984; Mikołajewska & Ivison 2001). The complication here is that the peak surface brightness corresponds to a brightness temperature of \((2-4) \times 10^7 \) K at 18 cm, implying a similar lower limit to the physical temperature of a thermally-emitting plasma.

The distribution of the flux density perpendicular to the jet is shown in Figure 3b, which suggests that the spectral index is indeed almost flat throughout the ruff, and further shows that the emission extends to 2.40 mas at our sensitivity, or ~ 120 (d/3 kpc) AU. Note also that the ruff is roughly symmetric about the jet.

3.4. Implications for X-ray emission

If the radio emission is bremsstrahlung from a thermal population of particles then that same population should
co-spatially emit X-rays. The X-ray luminosity is given by \( L_X = l_{rad} \times \exp(-\hbar \nu / kT) \) where \( T \) is the temperature of the particles (approximated to be the radio brightness temperature), \( k \) and \( \hbar \) are the Boltzmann and Planck constants, \( \nu \) is the lower frequency of the X-rays whose luminosity \( L_X \) is predicted from the radio luminosity \( l_{rad} \). We measure a brightness temperature \( T_B \approx 10^5 \) K which over-predicts the X-ray luminosity compared with that observed (Margon 1984). Allowing for a significant fraction of the observed X-rays being emitted by the jets means the discrepancy could be as much as an order of magnitude. This could in principle be due to the presence of neutral material in the vicinity of the muf which would absorb X-rays but not radio emission. Alternatively, it may suggest that the particle population is not Maxwellian.

4. The origin of the smooth emission

4.1. Theoretical background

The most straightforward interpretation of the radio emission is that it arises from mass outflow from the binary system that is enhanced towards the orbital plane. Such mass loss could either (i) come from the companion (most likely an O or B star), (ii) be a disk wind from the outer parts of the accretion disk or (iii) arise from mass loss from a proto-common envelope surrounding the binary components. The detection of this mass loss may have rather important implications for our understanding of the evolutionary state of this unique system. It has been a long-standing puzzle how SS 433 can survive so long in a phase of extreme mass transfer (\( \dot{M} \gtrsim 10^{-5} M_\odot \text{ yr}^{-1} \)) without entering into a common envelope phase where the compact object spirals completely into the massive companion (for a recent discussion see King, Taam & Begelman 2000). Since the theoretically predicted mass-transfer rate exceeds even the estimated mass-loss rate in the jets (\( \dot{M} \sim 10^{-3} M_\odot \text{ yr}^{-1} \); Begelman et al. 1980), King et al. (2000) proposed that most of this transferred mass is lost from the system in a radiation-pressure driven wind from the outer parts of the accretion disk (see also King & Begelman 1999). A related problem exists in some intermediate-mass X-ray binaries (IMXBs): Models of the IMXB Cyg X-2 (King & Ritter 1999; Podsiadlowski & Rappaport 2000; Kolb et al. 2000; Tauris, van den Heuvel & Savonije 2000) show that the system must have passed through a phase where the mass-transfer rate was \( \sim 10^{-5} M_\odot \text{ yr}^{-1} \), exceeding the Eddington luminosity of the accreting star by many orders of magnitude, without entering into a common-envelope phase, and where almost all the transferred mass must have been lost from the system. The observed emission in SS 433 presented here may provide direct evidence of how such mass loss takes place.

4.2. Evidence for mass out-flows

The existence of a disk-like outflow was first postulated by Zwitter, Calvani, & D’Odorico (1991) to explain the variation with precession phase of the secondary minimum in the photometric light curve. Fabrika (1993) proposed a disk-like expanding envelope caused by mass-loss from the outer Lagrangian point L2 to explain the blue-shifted absorption lines of H I, He I and Fe II (see also Maranano, Ciatti & Vittone 1980), whose spectrum shows that all the emission lines seen in SS 433 have P-Cygni profiles indicating the presence of outflowing gas. Filipenko et al. (1988) observe a remarkable double peaked structure for the Paschen lines, with speeds close to 300 km s\(^{-1}\).

4.3. Estimates of \( \dot{M} \) and the windspeed

If we assume that the observed radio emission is due to bremsstrahlung, we can obtain a rough estimate for the mass-loss rate, \( \dot{M} \), in this equatorial outflow. For this purpose, we assume that the outflow is radial but confined to an angle \( \alpha \) with respect to the orbital plane of the binary. For a simple wind mass-loss law, the mass density, \( \rho \), of the outflow then depends on the distance \( r \) from the system according to \( \rho = \dot{M} / (4 \pi \sin \alpha^2 v_{\infty}) \), where \( v_{\infty} \) is the outflow velocity at infinity. At a particular radio frequency \( \nu \), the outflow will be optically thick to some distance \( r_{\nu} \).

Assuming that we see all the radio emission from the optically thin part of the outflow and are observing the system close to the orbital plane (both assumptions are only approximately true and ignore geometrical complications), a rough estimate for the mass-outflow rate is

\[
\dot{M} \sim 1.6 \times 10^{-4} M_\odot \text{ yr}^{-1}
\]

\[
\times \frac{3^{1/4}}{d_3} \frac{2}{3^{1/2} v_{300}^{-1/2}} \frac{1/2}{1/2} \left( \sin \alpha_{30}^{-1/4} \right)
\]

where \( S_{30} = S_{o} / 30 \mu Jy \), \( d_3 = d / 3 \text{kpc} \), \( v_{300} = v_{\infty} / 300 \text{ km s}^{-1} \), \( v_{30} = v_{\nu} / 1.4 \text{ GHz} \), \( g_{10} = g / 10 \) (\( g \) is the Gaunt factor for free-free emission; see e.g., Rybicki & Lightman 1979), \( \sin \alpha_{30} = \sin \alpha / \sin 30^\circ \).

One of the major uncertainties in this estimate is the velocity of the outflow, though a velocity of \( \sim 300 \text{ km s}^{-1} \) is similar to that of the lines by Filipenko et al. (1988) and is close to the characteristic orbital velocity of SS 433, as one might expect for an outflow from the binary system rather than either binary component. Furthermore, if this outflow started soon after the supernova explosion which formed the compact object \( \sim 10^6 \text{ yr} \) ago and whose impressively circular remnant is seen clearly in the images of Dubner et al. (1988), a velocity of \( \sim 300 \text{ km s}^{-1} \) implies an extent of the outflow of \( \sim 3 \text{ arcmin} \) (for \( d = 3 \text{kpc} \)). Indeed, this is exactly the size of the extended smooth emission seen by Dubner et al. (1998) and suggests that this may be the outer extent of the same outflow.

The above estimate for \( \dot{M} \) would imply that the outflow is optically thick at a frequency of \( \sim 1 \text{ GHz} \) to a distance of \( r \sim 10^{15} \mu \text{m} \) and that the radio emission from the central region of the jet would be somewhat attenuated (although this will also depend on the exact geometry of the outflow and its orientation to the line of sight).

It also suggests that the outflow is moderately optically thick in the optical and that part of the observed visual extinction to the system (\( A_V = 7.8 \), Margon 1984) may be due to the outflow, as postulated by Zwitter et al. (1991).

The inferred mass-loss rate, \( \dot{M} \sim 10^{-4} M_\odot \text{ yr}^{-1} \), is much higher than any reasonable mass-loss rate from an O-star primary and suggests that it is connected with the unusual short-lived phase SS 433 is experiencing (see § 4.1). It could be mass loss from a common envelope that has already started to form around the binary, or a hot coronal wind from the outer parts of the accretion disk driven, e.g., by the X-ray irradiation from the central compact source.
5. SUMMARY

With unique sampling in the UV-plane, we have imaged the SS 433 system at 6 cm and 20 cm and securely detected at both wavelengths smooth emission extending over a few hundred AU perpendicular to the jet axis. The most likely interpretation of this radiation is emission from matter which has been ejected from the disk as a thermal wind with an outward speed of $\sim 300\,\text{km}\,\text{s}^{-1}$.

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Fig. 3.— a: The total flux density in the ‘ruff’ emission as a function of frequency (see text). Crosses: northern emission; triangles: southern emission; filled circles: sum of northern and southern emission. b: The flux density integrated over 40 mas strips parallel to the jet, as a function of distance perpendicular to the jet, at 10 mas resolution. The solid line is 18 cm, the dotted line the 6 cm data. Note the flat spectrum of the ‘ruff’ emission, compared to the inverted spectrum of the (self-absorbed) jet core.