SS 433: a WR X-ray binary or a WR-type phenomenon?

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Abstract. We present mid-infrared spectra of the microquasar SS 433 obtained with the Infrared Space Observatory (spectroscopic mode of ISOPHOT) and compare them to the spectra of four Wolf-Rayet stars. The mid-infrared spectrum of SS 433 shows mainly H\textsc{i} and He\textsc{i} emission lines and is very similar to the spectrum of WR 147, a WN8(h)+B0.5V binary with a colliding wind. The 2–12 µm continuum emission corresponds to optically thin and partially optically thick free-free emission from which we calculate a mass loss rate of $1.4 - 2.2 \times 10^{-4} M_\odot \text{yr}^{-1}$ if the wind is homogeneous and a third of these values if it is clumped, which is consistent with a strong WN stellar wind. We propose that this strong wind outflows from a geometrically thick envelope of material surrounding the compact object like a stellar atmosphere, imitating the Wolf-Rayet phenomenon.

1. Introduction

SS 433 is a microquasar, i.e. an X-ray binary with relativistic jets, which shows a very peculiar optical spectrum (Margon 1984): there are the so-called “stationary” emission lines, including strong H\textalpha lines, showing normal Doppler shift movements with a period of 13 days, and the less intense “moving” lines with huge Doppler shifts corresponding to relativistic velocities with a period of about 162 days. The latter are formed in relativistic jets which undergo a precession movement in 162 days. The parameters of this system are: $P_{\text{orb}} = 13.08 \text{ d}$, $P_{\text{prec}} = 162.375 \pm 0.011 \text{ d}$, velocity of the ejections $v = 0.2647 \pm 0.0008 \text{ c}$, inclination of the jet axis to the line of sight $i = 78.05^\circ \pm 0.5^\circ$ and opening angle of the precession cone $\theta = 20.93^\circ \pm 0.08^\circ$ (Eikenberry et al. 2001). The ejections and their precession movement are indeed observed in the radio images (Hjellming & Johnston 1981). SS 433 is the only microquasar with continuous ejections and which shows evidence of ions accelerated to relativistic velocities (0.26c). Despite intensive studies, the nature of the two stars in this binary system remains unknown. The presence of Wolf-Rayet-like lines added to the very luminous continuum in the visible and near-IR ranges led to associate the donor star to a Wolf-Rayet or Of star (Murdin et al. 1980; van den Heuvel et al. 1980).

2. Observations

We use observations of SS 433 (R.A. = 19h 11m 49s.57, Dec. = +04° 58′ 57″.8 in J2000) from the archives of the Infrared Space Observatory (ISO). The ob-
Table 1. Main properties of the WR stars to be compared with SS 433.

| Name   | WR type | binary | distance | $A_V$ | reference                  |
|--------|---------|--------|----------|-------|---------------------------|
| WR 78  | WN7h    | no     | 2.0 kpc  | 1.48–1.87 | Crowther et al. (1995)    |
| WR 134 | WN6     | possible | 2.1 kpc | 1.22–1.99 | Morel et al. (1999)       |
| WR 136 | WN6(h) | possible | 1.8 kpc | 1.35–2.25 | Stevens & Howarth (1999)  |
| WR 147 | WN8(h) WNL | B0.5 V | 630 ± 70 pc | 11.2 | Morris et al. (2000)     |

Observations shown here were achieved with the spectroscopic modes of ISOPHOT (Lemke et al. 1996) the photometer on board ISO. We also searched in the ISO archives for observations of WR-type stars, particularly those of WN-type which are less evolved and so still emit hydrogen lines. We found four WN stars (see Table 1) observed with ISOSWS, and the spectra were degraded to the ISOPHOT spectral resolution (FWHM $\sim$ 0.04 & 0.1 $\mu$m for the 2–5 $\mu$m and 6–12 $\mu$m ranges respectively). See Fuchs et al. (2004) for the details about data analysis.

2.1. The emission lines: comparison with Wolf-Rayet stars

Fig. 1 shows the observed spectra (i.e. with no correction of absorption by the interstellar medium) of SS 433 on 1997 April 11 and of the four WN stars. No absorption line was found. The emission lines are mainly H\textsc{i} lines blended with He\textsc{i} or He\textsc{ii} lines. No metallic line is detected. It is clear in Fig. 1 that the spectrum of SS 433 is closest to the one of WR 147, a WN8(h) star, it shows the same general shape with the same lines and comparable relative intensities between the latters, except for the 10.5 $\mu$m line which is absent in SS 433. However, Smith & Houck (2001) studied 8–13 $\mu$m spectra of several WN8 and WN9 stars where this 10.5 $\mu$m line can be very weak or absent. Thus in the mid-IR SS 433 looks like a late WN star (WN8) or later type, which is relatively H-rich. Note that WR 147 is a Wolf-Rayet binary (WN8+B0.5V) system with a strong colliding wind that has been observed in radio (Williams et al. 1997).

2.2. The continuum

The spectra were dereddened using the Lutz et al. (1996) law and $A_V=8$ (see Fuchs et al. 2004 for the details). The continuum of SS 433 in April 1997 can be very well fitted by one or two power laws and a blackbody emission as shown in Fig. 1 (right). On 1997 April 11 the continuum corresponds to a power law from 2.5 to 12 $\mu$m: $F_\nu = C \lambda^{-\alpha}$ Jy where $C=2.3$ and $-\alpha=-0.6$. Then a blackbody model with $T=150$K and $R=7000R_\odot$ is added to this power law to fit the far-IR emission, but with only three points at 12, 25 and 60 $\mu$m the constraints are not strong. The two other April 1997 spectra are fitted by two power laws with spectral index: $-\alpha=+0.1$ and $-0.6$ on April 17, and $-\alpha=+0.3$ and $-0.6$ on April 23 for the 2–4.5 $\mu$m and 4.5–12 $\mu$m range respectively.

These power laws can be interpreted as free-free emission: optically thin for the positive slopes between 2 and 4.5 $\mu$m in April 17 and 23, and the negative slope ($\lambda^{-0.6}$) corresponding to the intermediate regime between optically thin and optically thick free-free emission. This $-0.6$ slope is the exact theoretical spectral index for the free-free emission from an ionized homogeneous wind outflowing from a star with a spherical expansion and at a constant velocity (Wright & Barlow 1973). This kind of wind is very common for O or WR
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Figure 1. Left: Observed (i.e. absorption not corrected) spectra of SS 433 with ISOPHOT-S on 1997 April 11 and of four Wolf-Rayet stars with ISOSWS rebinned to the PHOT-S resolution and wavelength range. Right: Fit of the continuum emission of the dereddened spectra of SS 433 with power laws and a blackbody emission (at 4.6 kpc) as indicated.

stars (Cohen et al. 1975). Note that Schmid-Burgk (1982) demonstrated that the overall spectral emitting behaviour is the same for non spherical outflows with more complex geometries as long as they stay thick. The far-IR emission is likely thermal emission from dust at $T = 150$ K surrounding the system at a large distance ($R > 7000 R_\odot$).

2.3. Mass loss evaluation

From our fit of the free-free emission of SS 433 we can calculate the corresponding mass loss $\dot{M}$ using the Wright & Barlow (1975) equation (8). Except for the flux density at 5 $\mu$m ($\nu$=60 000 GHz) in the maximum and minimum levels of April 1997 ($F_\nu$=876 mJy & 495 mJy) and the distance $D=4.6$ kpc, the parameters of the wind are not very well known. We took the usual or average values of the WN winds, assuming that the Gaunt factor is $g=1$, the terminal velocity of the wind is $v_\infty=1000$ km s$^{-1}$ (Crowther 2003a) and using a wind composition typical of late WN stars: mean atomic weight per nucleon $\mu=2$, number of free electrons per nucleon $\gamma_e=1$ and mean ionic charge $Z=1$ (Leitherer et al. 1997). We find a mass loss rate of $\dot{M} = 1.43 - 2.19 \times 10^{-4} M_\odot$ yr$^{-1}$. We explored the possible range of the parameters to see how they influence the resulting mass loss. The greatest uncertainties come from the wind velocity and the Gaunt factor so that our result is valid within a factor of 2. This result is in good agreement with the past estimates of $10^{-5} - 10^{-4} M_\odot$ yr$^{-1}$ (Shklovskii 1981; van den Heuvel 1981; King et al. 2000).
However, the mass loss rate of SS 433 has to be corrected from the effect due to the very likely inhomogeneity of the wind. Clump mass loss rate of WN stars are a factor of 3 times lower (Crowther 2003a) thus we get $4.7 - 7.3 \times 10^{-5} \, M_\odot \, yr^{-1}$ for SS 433. This result can be compared to the mass loss rate of WR 147 measured by Morris et al. (2000): $1.5 - 3.7 \times 10^{-5} \, M_\odot \, yr^{-1}$ and to the typical range of WN clumped mass-loss rates: $10^{-5.5} - 10^{-4.5} \, M_\odot \, yr^{-1}$ (Crowther 2003b). Thus the mass loss rate found for SS 433 is compatible with a strong WN wind.

With such a huge mass loss one could ask what happens to all this ejected material. The relativistic jets of SS 433 are well known and the source is continuously ejecting material in this way, but Marshall et al. (2002) and previous studies estimated to $\sim 10^{-7} \, M_\odot \, yr^{-1}$ the mass loss of these jets, so negligible compared to the IR wind. A part of this wind material probably forms dust at $T \sim 150$ K and $R > 32.6$ AU, which then emits in the far infrared as we observe for $\lambda > 15 \, \mu m$ in the 1997 April 11 spectrum (Fig. 1 right). The IR wind is also probably responsible for the equatorial outflows observed in radio at larger distances ($30 – 70$ mas $\sim 140 – 300$ AU, Paragi et al. 1999; Blundell et al. 2001) perpendicularly to the jet.

3. Discussion

We showed that both the emission lines and the continuum of the mid-IR spectrum of SS 433 are compatible with a Wolf-Rayet type for the donor star, and preferably a late WN star (WN8 or later). However, the recent discovery of Gies et al. (2002) and Hillwig et al. (2004) of absorption features in the blue spectrum of SS 433 suggests that the donor star is an A3-7I supergiant star with $10.9 \pm 3.1 \, M_\odot$. On another hand, Lopez et al. (2004) modelling the Chandra X-ray spectrum during eclipse constrain the radius of the mass donor star to be $9.1 \pm 1.0$ R$_\odot$, which corresponds to O6-O8 main sequence stars with $29 \pm 7 \, M_\odot$ and $T = 41000 - 35800$ K (Lanec 1992). But such a radius could also correspond to a B4-5 giant star ($R = 8 \, R_\odot$, $M = 7 \, M_\odot$ and $T = 15000$ K for a B5 III). Note that this constraint on the radius found by Lopez et al. (2004) is not incompatible with the radius of a Wolf-Rayet star, however if the results of Hillwig et al. (2004) are confirmed then the donor star is not a Wolf-Rayet star and thus there is a phenomenon imitating such a star in SS 433.

Before we discuss this point, let us see which constraints on the nature of the donor star we can provide from the mid-IR spectra of SS 433. We modeled the possible donor stars with black body emissions at a distance of 4.6 kpc. Both a giant B5 star and a main sequence O6-O8 star have negligible emission compared to the optically thin ISOPHOT flux density of the continuum and thus they are compatible with the spectrum of SS 433. But the emission of an A7I ($T=8150$ K, $R = 60 \, R_\odot$) is not compatible unless its radius is $< 30 \, R_\odot$. Then this constraint is compatible with the result of Hillwig et al. (2004) who find the radius of the Roche lobe volume for the mass donor star to be $R_L = 28 \pm 2 \, R_\odot$. Note that this corresponds to a star with an intermediate size between type I (supergiant) and type II (bright giant) stars.

Now, if the mass donor star of SS 433 is not a Wolf-Rayet star, then there is a phenomenon imitating the emission of such a star in this binary system. We propose that this phenomenon comes from the material surrounding the compact
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object: this material does not form a classical thin accretion disc but rather a thick torus or a thick envelope like a stellar atmosphere, which is ionized by the X-rays emitted in the close vicinity of the compact object and expelled by radiation pressure, thus imitating the wind of a Wolf-Rayet star. There may be a “classical” thin accretion disc but only very close to the compact object and not detectable because of the surrounding material. This would explain that there is no evidence for an accretion disc in the Chandra X-ray spectrum of SS 433 according to [Marshall et al. (2002)] and that SS 433 is not a strong X-ray source as the others microquasars or X-ray transients. As Cyg X-3 showed very similar results to those of SS 433 concerning the IR spectrum and corresponding mass loss ([Koch-Miramond et al. 2002]) we could ask ourselves about the possibility of Wolf-Rayet imitation in this X-ray binary too.

References

Blundell, K. M., Mioduszewski, A. J., Muxlow, T. W. B., Podsiałdowski, P., & Rupen, M. P. 2001, ApJ, 562, L79
Cohen, M., Kuhfu, L. V., & Barlow, M. J. 1975, A&A, 40, 291
Crowther, P. A. 2003a, in Massive Stars: Formation, Evolution and Environment, ed. Heydari-Malayeri & Zahn, astro-ph/0305141
Crowther, P. A. 2003b, in A Massive Star Odyssey: From Main Sequence to Supernova, ed. K. van der Hucht, A. Herrero, & E. César (ASP), 47
Crowther, P. A., Hillier, D. J., & Smith, L. J. 1995, A&A, 293, 403
Eikenberry, S. S., Cameron, P. B., Fierce, B. W., et al. 2001, ApJ, 561, 1027
Fuchs, Y., Koch Miramond, L., & Ábrahám, P. 2004, A&A submitted
Gies, D. R., Huang, W., & McSwain, M. V. 2002, ApJ, 578, L67
Hillwig, T. C., Gies, D. R., Huang, W., et al. 2004, ApJ accepted, astro-ph/0403634
Hjellming, R. M. & Johnston, K. J. 1981, ApJ, 246, L141
King, A. R., Taam, R. E., & Begelman, M. C. 2000, ApJ, 530, L25
Koch-Miramond, L., Ábrahám, P., Fuchs, Y., Bonnet-Bidaud, J.-M., & Claret, A. 2002, A&A, 396, 877
Lang, K. R. 1992, Astrophysical Data I. Planets and Stars. (Springer-Verlag)
Leitherer, C., Chapman, J. M., & Koribalski, B. 1997, ApJ, 481, 898
Lemke, D., Klaas, U., Abolins, J., et al. 1996, A&A, 315, L64
Lopez, L. A., Marshall, H. L., Canizares, C. R., Kane, J. F., & Schulz, N. S. 2004, in 35th COSPAR,2004, Advances in Space Research (Elsevier Science Ltd)
Lutz, D., Feuchtgruber, H., Genzel, R., et al. 1996, A&A, 315, L269
Margon, B. 1984, ARA&A, 22, 507
Marshall, H. L., Canizares, C. R., & Schulz, N. S. 2002, ApJ, 564, 941
Morel, T., Marchenko, S. V., Eenens, P. R. J., et al. 1999, ApJ, 518, 428
Morris, P. W., van der Hucht, K. A., Crowther, P. A., et al. 2000, A&A, 353, 624
Murdin, P., Clark, D. H., & Martin, P. G. 1980, MNRAS, 193, 135
Paragi, Z., Vermeulen, R. C., Fejes, I., et al. 1999, A&A, 348, 910
Schmid-Burgk, J. 1982, A&A, 108, 169
Shklovskii, I. S. 1981, Soviet Astronomy, 25, 315
Smith, J. D. T. & Houck, J. R. 2001, AJ, 121, 2115
Stevens, I. R. & Howarth, I. D. 1999, MNRAS, 302, 549
van den Heuvel, E. P. J. 1981, Vistas in Astronomy, 25, 95
van den Heuvel, E. P. J., Ostriker, J. P., & Petterson, J. A. 1980, A&A, 81, L7
Williams, P. M., Dougherty, S. M., Davis, R. J., et al. 1997, MNRAS, 289, 10
Wright, A. E. & Barlow, M. J. 1975, MNRAS, 170, 41