SS 433: the second Wolf-Rayet X-ray binary?

Y. Fuchs\textsuperscript{1,2}, L. Koch-Miramond \textsuperscript{1} & P. Ábrahám\textsuperscript{3}

\textsuperscript{1} Service d’Astrophysique, CEA/Saclay, bat. 709, 91191 Gif sur Yvette cedex, France.
\textsuperscript{2} Université Paris VII, UFR de Physique, 5 place Jussieu, 75005 Paris, France.
\textsuperscript{3} Konkoly Observatory, P.O. box 67, 1525 Budapest, Hungary

Abstract. We present mid-infrared spectrophotometric observations of SS 433 with ISOPHOT. The He\textsuperscript{i}+He\textsuperscript{ii} lines in both spectra of SS 433 and of the Wolf-Rayet star WR 147, a wind-colliding WN8+BO5 binary system, closely match. The 2.5-12 \(\mu\)m continuum radiation is due to an expanding wind free-free emission in an intermediate case between optically thick and optically thin regimes. The inferred mass loss rate evaluation gives \(\sim 10^{-4} \odot \text{yr}^{-1}\). Our results are consistent with a Wolf-Rayet-like companion to the compact object in SS 433. A similar study for Cygnus X-3 confirms the Wolf-Rayet-like nature of its companion, although with a later WN type than previously suggested.

1. The mysterious SS 433 system

SS 433 has been discovered as a source of strong H\textalpha lines, and as a variable radio and X-ray source \cite{1}. It is an X-ray binary with a \(\sim 13\) days period, producing bipolar relativistic (0.26 c) jets undergoing a precession movement in \(\sim 162.5\) days, so covering a cone with an opening angle of 19.8\(^{\circ}\) and an axis of \(\sim 78.8\(^{\circ}\) with the line of sight. This precession has indeed been observed in radio, at arcsec \cite{2} and milliarcsec scales \cite{3}. So SS 433 was actually the first microquasar discovered. In spite of intensive studies, no line has been associated to the companion star yet. It is generally accepted but has never been proved that SS 433 is a neutron star + massive star binary system.

2. Mid-IR observations of SS 433

2.1. Comparison with Wolf-Rayet stars spectra

SS 433 has been observed with ISOPHOT, in the spectral mode at 2.5-5 \(\mu\)m (\(\sim 0.04 \mu\)m resolution) and 6-12 \(\mu\)m (\(\sim 0.1 \mu\)m resolution), and in the photometric mode at 12, 25 and 60 \(\mu\)m, in November 1996 and April 1997. We looked for Wolf-Rayet (WR) star observations in the ISO archives, as it was the suspected type for SS 433 companion star. Several WRs were observed with ISOSWS, and so we rebinned the SWS spectra to the spectral resolution of ISOPHOT.

As a lot of hydrogen is seen in SS 433 optical spectra, we chose to compare it to WRs of nitrogen type (WN) which are in the first stage of WR evolution. Figure \ref{fig1} (left) shows the observed spectra of the four corresponding WRs, classified from the not very evolved (late type WNL) to the evolved (early type WNE) ones: WR 147 \(\leftrightarrow\) WN8+Bo5 (WNL), WR 78 \(\leftrightarrow\) WN7h (WNL), WR 136 \(\leftrightarrow\) WN6b (WNE) and WR 134 \(\leftrightarrow\) WN6 (WNE). Comparing on figure 1 these spectra to the one of SS 433, it is clear that SS 433 is closest to WR 147, a late type WR.
Figure 1. Left: Comparison of SS 433 observed spectra with that of Wolf-Rayet stars (of WN type). Right: Comparison of WR 147 dereddened spectrum with the ones of SS 433 taken at different precession phases ($\Phi_p$) and orbital phases ($\varphi$). Lines are identified according to [5].

Figure 1 (right) also shows the comparison of WR 147 spectrum with that of SS 433 taken at different phases. SS 433 and WR 147 spectra were dereddened with $A_V = 8$ and 11.2 mag respectively, using the Lutz et al. [4] law. The lines, identified according to [5], are strong and weak H+He I blended lines (because of ISOPHOT spectral resolution) and weak He II lines. No metallic line was observed. The SS 433 line spectrum is clearly WR-like. We note that WR 147 is known as a colliding wind binary system which may explain its resemblance to SS 433.

2.2. Continuum

Figure 2 shows the continuum spectra of SS 433, which flux density ($F_\nu$) is well fitted by power laws in the 2-12 $\mu$m range, corresponding to free-free emission: optically thin for $F_\nu \propto \lambda^{0.1}$, and in the intermediate regime between optically thin and thick for $F_\nu \propto \lambda^{-0.6}$. In far-IR, an additional component, as a black-body due to dust surrounding the system, is needed. The 0.6 spectral index is characteristic of an ionized homogeneous wind with a spherical expansion at a constant velocity [7], although it is also valid for a more complex geometry as long as it stays thick [4]. So SS 433 continuum spectrum corresponds to the one emitted by a standard O or WR wind.

2.3. Mass loss rate

We calculated the mass loss rate of this free-free emitting wind, following the Wright & Barlow [7] formula (8). With a distance $D = 3.5$ kpc, a Gaunt factor $g \sim 1$, a $F_\nu = 1000$ mJy flux at 4 $\mu$m ($7.5 \times 10^{13}$ Hz), and for a WN-type wind where
the mean atomic weight per nucleon $\mu = 1.5$, the number of free electrons per nucleon $\gamma = 1$, the mean ionic charge $Z = 1$ and the velocity $v_{\infty} = 1000 \text{ km.s}^{-1}$, we find: $M = 1.0 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1}$. However, the recent WN mass-loss rate estimates show that this value has to be lowered by a factor 2 or 3 due to clumping in the wind. This is in good agreement with the mass transfer rate estimated by van den Heuvel et al. assuming a normal homogeneous WR wind, or with the recent mass transfer values obtained from simulations of SS 433 evolution by King et al. For WR 147, $M \approx 1.5 - 3.7 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1}$ and the WN mean is $\sim 3 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1}$, so our $\sim 10^{-4} \text{ M}_\odot \text{ yr}^{-1}$ mass loss evaluation for SS 433 is compatible with a strong WNL wind.

What happens to the material contained in this wind is unknown since only $\sim 10^{-7} \text{ M}_\odot \text{ yr}^{-1}$ is ejected into the jets. It may be accreted then ejected via the L$_2$ point, or close to the compact object. It may then form dust seen in far-IR at a distance $>20$ a.u. This material is probably responsible for the equatorial outflows observed with the VLBA at $\sim 100$ a.u. from SS 433.

### 3. Cygnus X-3

Cygnus X-3 is a microquasar for which WR-like features have been detected in near-IR spectra. We also observed it with ISOPHOT-S during its quiescent state, but with much more difficulties as it is a weak IR source. Its spectrum was also compared to the four WR spectra as shown in figure 3. Only one line was found in Cygnus X-3 spectrum, at $4.3 \mu\text{m}$ with a confidence level of more than $4.3 \sigma$, corresponding to an HeI line only visible in WR 147 spectrum.
Fuchs, Koch-Miramond & Ábrahám

2.62 Br
3.09 HeII
3.73 HeI+Pf
4.05 Br α
4.30 HeI
4.65 Pf
7.46 Pf
10.5 [SIV]+HeI+HI

Figure 3. Observed spectra of Cygnus X-3 and four WR stars. An arbitrary vertical offset has been added to the WR spectra for clarity.

The spectral fitting of Cygnus X-3 dereddened (A_V = 20 mag) spectra is obtained with a unique power law F_ν ∝ λ^{-0.6} in the 2.4-12 µm range when dereddened with the Lutz et al. law (figure upper right), and with the sum of a power law with slope λ^{-1.6} and a black body, a hint for the presence of circumstellar dust, when using the Draine law (figure lower right). We cannot choose between these two laws since the molecular composition of the absorbing material on the line of sight to Cygnus X-3 is unknown. As for SS 433, the power law part of the continuum spectrum can be explained by free-free emission of an expanding wind in the intermediate case between optically thick and optically thin regimes. The corresponding mass loss evaluation, with 63 mJy at 6.75 µm and v_∞=1500 km.s^{-1}, gives M = 1.2 × 10^{-4} M_ʘ yr^{-1}. We conclude that our results are consistent with a Wolf-Rayet companion to the compact object in Cygnus X-3 of WN8 type, a later type than suggested by previous works.

4. Conclusion

SS 433 shows a WNS-like spectrum, which continuum is due to free-free emission corresponding to a standard O or WR wind or a geometrically complex thick wind. The inferred mass loss of ∼ 10^{-4} M_ʘ yr^{-1} is compatible with a WNL wind. So either SS 433 is the second Wolf-Rayet X-ray binary known in our Galaxy after Cygnus X-3, or it shows WR-like conditions, and at that point we cannot distinguish between these two cases.

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