SF2A 2008
C. Charbonnel, F. Combes and R. Samadi (eds)

THE CIRCUMBINARY DUSTY DISK OF UPSILON SGR REVEALED BY MID-IR INTERFEROMETRIC OBSERVATIONS WITH THE VLTI/MIDI

Bonneau, D.[1], Netolický, M.[4,2], Chesneau, O.[1], Harmanec, P.[3], Koubský, P.[4], Mourard , D.[1] and Stee, P.[1]

Abstract. The first mid-IR interferometric observations of a hydrogen-deficient binary star, υ Sgr, were carried out using the MIDI/VLTI instrument between April 2007 and May 2008. The dusty circumbinary envelope is resolved in the N band ($8 - 13.5\mu m$), and has a typical size of 20 x 14 mas. The calibrated fringe visibilities, the mid-IR spectrum and the SED were fitted using models computed with the radiative transfer code MC3D using several mixtures of carbon and silicate dust, in order to determine the geometry and chemical composition of the envelope. The best model we obtain is a geometrically thin and dense disk with an inner radius of $R_{in} \simeq 6.0$AU and a scale height $h_{100} \simeq 3.5$AU. The inclination of the disk is $i \simeq 50^\circ$ and its position angle is $PA \simeq 80^\circ$. The chemical composition of the dust is approximatelya ratio of 60% of carbon dust and 40% of silicate dust. We constrained for the first time the geometry and the chemistry of the circumbinary dusty envelope of υ Sgr. It is now clear that the components of υ Sgr are massive stars ($> 10\ M_\odot$) and the results are compatible with evolutionary scenario proposed by Delgado & Thomas (1981) of a binary with massive components experiencing several phases of important mass transfer leading to the hydrogen-deficient primary star. However, complementary spectro-interferometric observations in the near infrared and the visible are mandatory to investigate the complex structure of the inner circumstellar environment and directly resolve the stellar components of the υ Sgr system.

1 Introduction

The massive, hot and very luminous stars are the principal source of UV flux in the Galaxy and their evolution is affected by a powerful stellar wind which has effects on the circumstellar medium and the stellar formation. The determination of the fundamental parameters of massive stars suffers from a great uncertainty. Close massive binary stars are complex objects as well from the observational point of view as from the modeling point of view. The study of binary systems with (initially) massive objects is particularly attractive. Accretion discs, gaseous streams, jets, and scattering envelopes were found by combining spectroscopic, photometric and interferometric observations and studied in the well known interacting binary β Lyrae (Harmanec et al. 1996; Harmanec 2002; Ak et al. 2007). The system υ Sgr (HD 181615) with a A type low mass supergiant, is the brightest member of the type of extremely hydrogen-deficient binaries stars (HdB stars; Schönberner & Drilling 1983). The HdB stars are in a second phase of mass transfer where the primary has ended the core helium burning phase (Delgado & Thomas 1981). The distance of υ Sgr determined by Hipparcos was recently revised to $d = 595^{+94}_{-72}$ pc (van Leeuwen 2007). The system υ Sgr is known as a single-lined spectroscopic binary ($P =$ 137.9 d, $e = 0.0$, $dP/dt =$ -24 s/y; Koubský et al. 2006). The secondary orbit was determined from the study of the IUE spectra ($M_p/M_s \approx 0.64$; Dudley & Jeffery 1990), however, the detection of the secondary lines is uncertain due to the poor quality of the data. The presence of circumstellar matter in the υ Sgr system is evidenced by the complex Hα absorption/emission profiles but also by the strong infrared excess, and in particular by the prominent silicate dust signature at 9.7μm (Treffers et al. 1976). Nariai (1967) proposed that the displaced Hα absorption is formed in a supersonic flow generated as the gas is transferred from the primary via the L1 point, adopts a

[1] UMR 6525 H. Fizeau, Univ. Nice Sophia Antipolis, CNRS, OCA, Av. Copernic, F-06130 Grasse, France
[2] Masaryk University, Department of Theoretical Physics and Astrophysics, 611 37 Brno, Czech Republic
[3] Astronomical Institute of the Charles University, V Holešovičkách 2, 180 00 Praha 8, Czech Republic
[4] Astronomical Institute of the Academy of Sciences, 251 65 Ondřejov, Czech Republic

form of a cone directed toward the secondary and partly escapes from the system in the form of an outflowing spiral arm encircling the whole binary. Koubský et al. (2006) have tentatively suggested an alternative model in which υ Sgr might be a non-eclipsing analog of the β Lyr system (the peculiar spectrum of the primary would come from the rim of a disk, while the blue-shifted absorption would originate from the slowly precessing bipolar jets). This paper presents the first detection of the dusty circumbinary envelope of υ Sgr and the best model obtained from interferometric and photometric data using the MC3D code.

2 Mid-Infrared observations

2.1 Interferometric Observations

The observations were carried out with the instrument MIDI of the Very Large Telescope Interferometer (VLTI) in operation at the ESO Paranal Observatory (Leinert et al. 2003), using the 1.8m Auxiliary Telescopes (ATs) and 8m Unit Telescopes (UTs). υ Sgr was observed from April till August 2007 and in May 2008 with 6 baselines ranging from 20 meters up to 125 meters. The observations were performed using the PRISM dispersive element giving a spectral resolution of $R \sim 30$ in the N-band. In order to calibrate the visibilities of the science target, we used observations of calibrating stars selected from the MIDI calibrator list using the SearchCal tool available at JMMC[1]. The data obtained with MIDI instrument have been reduced using IDL-based MIA+EWS software. A description of the data reduction steps can be found in Leinert et al. (2004). We have followed the standard reduction process. As seen in Fig. 1-Left, the dataset offers a reasonable coverage of the u-v space, but there is only 1 measurement in position angle range from $90^\circ - 180^\circ$ which is the main source of uncertainty for the determination of the orientation and inclination angles derived from the observed visibilities.

2.2 First results

The images recorded using the MIDI star acquisition modes at 8.7 μm clearly show a perfect Airy pattern, which FWHM is $\approx 225\ mas$ meaning that υ Sgr is unresolved at the UTs focus ($D = 8.2m, 1.22\lambda/D = 0.267''$). On the other hand, the decrease of the visibility with increasing base length shows clearly that the dusty envelope of υ Sgr observed at $\lambda \sim 10\mu m$ is resolved by the VLTI. As a first-order model approximation of the source our calibrated visibility curves are fitted with 2D elliptical Gaussian with $FWHM \approx 20 \times 14mas$, inclination $i \approx 45^\circ$ and position angle $P.A. \approx 76^\circ$.

3 Radiative Transfer Modeling

The interferometric mid-IR calibrated visibilities have been combined with the spectral energy distribution (SED) to constrain the physical parameters of the dusty envelope of υ Sgr using a model computed with the radiative transfer code MC3D.

3.1 Photometric data of υ Sgr

For υ Sgr, we have adopted the value $E(\mathrm{B}-\mathrm{V}) = 0.20$ is adopted by Dudley & Jeffery (1990). Assuming $R_V = 3.1$, this color excess gives a total visual absorption $A_V \approx 0.6$. From this small value for the interstellar absorption and the large infrared excess of the source, it comes out that the circumstellar dust around υ Sgr should exhibit a small self-absorption. Given the asymmetry of the source, the dust cannot be distributed in a spherical shell but rather in a disk that does not intercept the line-of-sight and that must be seen at low or intermediate inclination.

The dereddened SED of υ Sgr was derived from UV, visual, near-IR and mid-IR measured flux compiled by Trams et al. (1991) can be fitted by two blackbodies (one for the stellar radiation at $T = 12000\,\mathrm{K}$, the other for the radiation from the dusty envelope at $T = 950\,\mathrm{K}$). We derived the luminosity of the central source $L \simeq 39000 L_\odot$ using the revised Hipparcos distance.

As suggested by the $10\,\mu$m feature present in the MIDI and IRAS spectra, we can expect some silicates in the dusty envelope of the binary. It might be inconsistent however, to restrict the chemical composition just to the silicate dust, as the primary source is now a HdB star.

[1] http://www.mariotti.fr/

parameter	value
$R_{\rm in}$ [AU]	$\simeq 6.0$
i	$\simeq 50^\circ$
α	$\simeq 2.0$
β	$\simeq 0.7$
h_{100} [AU]	$\simeq 3.5$
$\log(M_{\rm d}/M_\odot)$	≈ -3.5
$M_{\rm am.C}/M_{\rm d}$	$\simeq 0.6$

Table 1. Parameters of the best model visibility fit.

3.2 Visibility and photometry modeling

For the interpretation of the interferometric data and the observed SED, we used the MC3D radiative transfer code (Wolf et al. 1999) based on Monte-Carlo method for emitting, scattering, absorbing and reemitting the photons. The code assumes a spherical source located in the center of the coordinate system and spherical dust grains. The density of the dust shell is computed according to the model of the stratified dusty disk (Shakura & Sunyaev 1973), the density of witch is defined with the 2D law:

$$\varrho(r,z) = \varrho_{100}\Big(\frac{100}{r}\Big)^{\alpha} \exp\Big[-\frac{1}{2}\Big(\frac{z}{h(r)}\Big)^{2}\Big]$$

with $h(r) = h_{100}\big(\frac{r}{100}\big)^{\beta}$. r is the radial distance in the midplane of the disk, h_{100} is the scale height at the distance of $r = 100\,$AU, α the density parameter in the midplane and β is the vertical density parameter. The central source is described the effective temperature $T_{\rm eff}$ and the luminosity L (see Fig.1-Center). The MC3D code then makes it possible to calculate the SED and the intensity map of the source which is converted into visibility map. Computed SED and visibilities are fitted on the data to estimate the parameters of the best model. The dust is supposed to be a mixture of astronomical silicate and amorphous carbon. We assumed the grain size distribution of (Mathis et al. **?**) $\frac{{\rm d}n(a)}{{\rm d}a} \sim a^{-3.5}$, where a is the dust grain radius assumed to range from 0.01 to 1.00 μm. Because our poor current knowledge about the geometry of the binary orbit and its surrounding, the parameter space of the models we had to explore was large. The only fixed parameters were the parameters of the central source ($T_{\rm eff}$, $L/L_\odot$) and the sublimation temperature of 1500 K adopted for all the models. The outer radius of the model grid was kept to be $R_{\rm out} = 100\,$AU, which corresponds to a maximum angular size of $\sim 400mas$ consistent with the unresolved image taken with VLT UT telescope. The geometry of the disk is defined by α, β, h_{100}, $R_{\rm in}$, the inclination i and the $P.A.$, together with the composition and the total mass M_d of the dust. In the first step of the fitting procedure we focused on finding the brightness distribution on the sky giving the best fit of the visibilities, which are very sensitive to the geometry of the dusty envelope. In the second step, based on this best models we tried to find the best fit of the SED, taking a particular care of reproducing the 10μm silicate feature. The evaluation of the quality of the visibility fit was made using the reduced χ^2. The parameters of the best model are shown in Table 1. If we assume that the dusty disk lies in the same plane as the binary, the inclination of the model could put more constrains on the binary system. Our value for i is consistent with the constrains mentioned in Koubský et al. (2006). Also it would be noted that the $P.A.$ of the model is almost perpendicular to the observed orientation of the polarization $P_{\rm obs} = 172^\circ$ (Yudin 2001). The image of the disk given by the best model is shown in Fig.1-Right.

4 Conclusion

The VLTI-MIDI observations provided evidence for a thin, flat circumbinary disk around the hydrogen-deficient binary υ Sgr whose inner rim lies close to the radius of sublimation temperature. The chemical composition of the dust (60 % of carbon and 40% of silicate) could be a consequence of several episodes of mass transfers in agreement with the evolutionary scenario proposed by Delgado & Thomas 1981, leading to the hydrogen-deficient primary. These observations allowed us to constraint the the inclination and the position angle of the system, and given these constraints and the spectroscopic observations reported in Koubský et al. (2006), it is now clear that the components of υ Sgr are massive stars ($> 10\ M_\odot$). The results obtained here pushed the

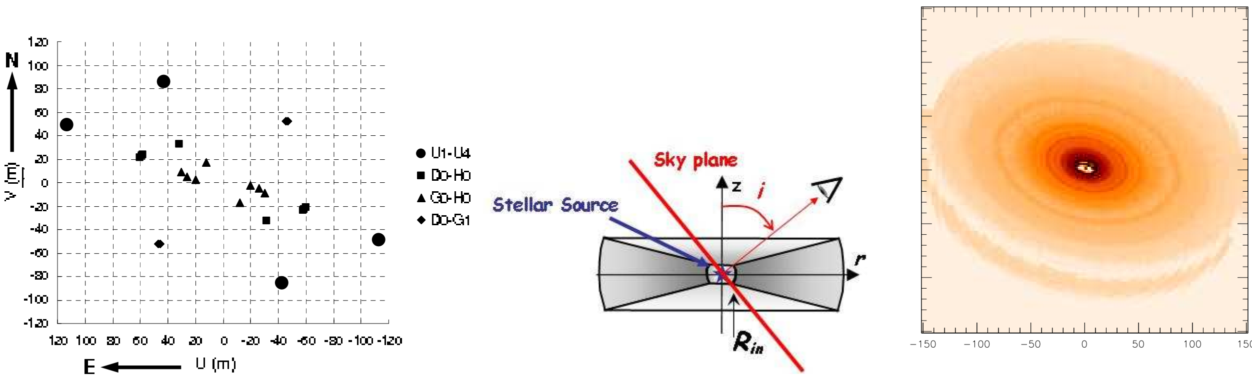

Fig. 1. Left: The *uv* coverage over the time of observations of the VLT baselines using UTs (U1-U4) and ATs (D0-H0, G0-H0, D0-G1). Center: Cut of the 3D model of disk used by the MC3D code. Right: The intensity map at 13 μm for the best visibility model. The intensity levels of the image corresponds to the square root of the real image.

knowledge of this peculiar HdB a step forward. However, there are still many open issues: e.g. the explanation of the peculiar spectrum of the 'invisible' component and the verification of the radial velocity curve of the secondary, that can be tested only at visible or UV wavelengths. The disk inner rim can be best studied in the near-IR using short baselines ($\leq$40m). The binary system, with a semi-major axis of $\sim 2mas - 4mas$, can be resolved with an interferometer, in the near-infrared (with baselines longer than ($\leq$80m), or better in the visible (continuum and some chosen lines) using the VEGA recombiner of the CHARA interferometer (Mourard et al. 2009).

Acknowledgements. The research of P. Harmanec was supported by the grants 205/06/0304, and 205/08/H005 of the Czech Science Foundation and also from the Research Program MSM0021620860 *Physical study of objects and processes in the solar system and in astrophysics* of the Ministry of Education of the Czech Republic. The visit of M. Netolický to OCA, where he was trained in modern VLTI software techniques and their application, was funded from the OPTICON grant R113-CT-2004-001566 JRA 4.

References

Ak, H., et al. 2007, A&A, 463, 233

Delgado, A. J., & Thomas, H.-C. 1981, A&A, 96, 142

Dudley, R.E., & Jeffery, C.S. 1990, MNRAS, 247, 400

Harmanec, P., Morand, F., Bonneau, D., et al. 1996, A&A, 312, 879

Hamanec, P. 2002, AN, 323, 87

Koubský, P., Harmanec, P., Yang, S., Netolicky, M., et al. 2006, A&A, 459, 849

Leinert, Ch., Graser, U., Przygodda, F., et al. 2003, Ap&SS, 286, 73

Leinert, Ch., van Boekel, R., Waters, L.B.F.M., et al. 2004, A&A, 423, 537

van Leeuwen, F., 2007, A&A, 474, 653

Mourard, D., Perraut, K., Bonneau D. et al. 2008, astroph

Nariai, K. 1967, PASJ, 19, 564

Schönberner & D., Drillind, J.S. 1983, ApJ, 268,225

Shakura, N. I., & Syunyaev, R. A. 1973, A&A, 24, 337

Trams, N.R., Waters, L.B.F.M., Lamers, H.J.G.L.M., et al. 1991, A&ASS 87, 361

Treffers, R., Woolf, N.J., Fink, U. and Larson, H.P. 1976, ApJ, 207, 680

Wolf, S., Henning, T., & Stecklum, B. 1999, A&A, 349, 839

Yudin, R. V. 2001, VizieR Online Data Catalog, 336, 80912