ON THE NATURE OF THE MICROQUASAR V4641 SAGITTARI

S. Chaty¹, I.F Mirabel², J. Martí³, and L.F. Rodríguez⁴

¹Department of Physics and Astronomy, The Open University, United Kingdom, s/chaty@open.ac.uk
²Service d’Astrophysique, DSM/DAPNIA/SAp, Centre d’Études de Saclay, France
³Instituto de Astronomía y Física del Espacio, Conicet, Argentina, mirabel@discovery.saclay.cea.fr
⁴Departamento de Física, Escuela Politécnica Superior, Universidad de Jaén, Spain, jmarti@ujaen.es

ABSTRACT

We present photometric and spectroscopic optical and near-infrared (NIR) observations taken during the outburst of the recently flaring source V4641 Sgr = SAX J1819.3-2525 (in’t Zand et al. 2000), on September 1999. This source was independently detected as the RXTE source XTE J1819-254 (Markwardt et al. 1999), and afterwards identified with the variable object V4641 Sgr (Kato et al. 1999). It underwent a bright optical outburst on 1999 Sept. 15.7 UT, going from magnitude 14 to 8.8 in the V-band (Stubbings 1999), and reaching 12.2 Crab in the X-rays (Smith et al. 1999) and Ks ≃ 13. This outburst was therefore bright, but very brief, with an e-fold decay time of 0.6 days. A radio source was resolved, making of V4641 Sgr a new microquasar (Hjellming et al. 2000). We discuss the nature of this system, showing that our observations suggest a distance farther than previously derived from the radio observations (Hjellming et al. 2000). The distance of the system would be between 3 and 8 kpc, the companion star being a B3-A2 main sequence star. Another possibility is that the companion star is crossing the Hertzsprung gap (type B3-A2 IV), and in this case the distance cited above would be the minimum distance of the system. The system is therefore an Intermediate or High Mass X-ray Binary System (IMXB or HMXB). The inconsistency regarding the distance between the radio and optical/NIR observations could be explained by the detection of an interaction between matter ejected before the X-ray outburst and the surrounding medium of the source. If this is confirmed, this source could be added to the short list of microquasars where such an interaction has been detected.

Key words: stars: individual: V4641 Sgr, X-rays: stars, infrared: stars.

1. INTRODUCTION

The source SAX J1819.3-2525 attracted considerable attention after the detection of a giant optical outburst on 1999 September 15.7 UT, from the magnitudes 14.0 to 8.8 in the V-band (Stubbings 1999). The source, in the direction of the galactic bulge, was centered on a star called V4641 Sgr in the catalog of variable stars and located in the constellation of Sagittarius (Kazarovets et al. 2000). Due to a confusion, most of the references of this X-ray source are reported to the name of GM Sgr. After this confusion was clarified by Williams (1999) and Samus et al. (1999), the source was newly designated V4641 Sgr (Kazarovets et al. 2000). The X-ray source XTE J1819-254 flared, from 1.6 to 12.2 Crab in the X-rays on 1999, September 14th, as observed by RXTE in the 2-12 keV band, through a brief but dramatic eruption (brightest source of X-rays in the sky), its position being coincident with the optical transient (Smith et al. 1999). Less than 10 hours later, the source was fainter than 50 mCrab. This source was identified with the previously detected faint X-ray transient, SAX J1819.3-2525, discovered by SAX on 1999, Feb 20th, (in’t Zand et al 1999) (energy 0.012 − 0.3 Crab), and independently detected by RXTE, on 1999, Feb 18th (Markwardt et al. 1999), with an energy between < 1 and 80 mCrab in the 2-10 keV energy band.

Kato et al. (1999) reported an unusual optical activity prior to this giant optical and X-ray outburst, through a ~ 1 mag high-amplitude modulation 6 days before the giant outburst (on Sep. 8th), and a quasi-periodicity of 2.5 days, which they claimed to correspond to the orbital period. Three other eruptions followed each lasting less than two hours in the X-rays, ones of the fastest bursts ever seen. The observations by RXTE (Wijnands & van der Klis 2000) allowed to observe some strong flaring activity: fluctuations by a factor of 4 on the timescale of seconds, and 500 on minutes. No QPO was detected, but some red noise at < 30 Hz was present.
The observations by SAX (in’t Zand et al. 2000) gave a best fit for the column density of \( N(H) \sim 0.05 \pm 0.02 \times 10^{22} \text{cm}^{-2} \).

The VLA radio telescope detected on Sept. 16.02 UT a strong radio source of 0.4 Jy at 4.9 GHz, at the position of the variable star, at \( \alpha = 18^h19^m21.636, \delta = -25^\circ 24' 25.6'' \) (J2000) (Hjellming et al. 1999a). The galactic coordinates are \((l,b) = (6.774015^\circ, -4.789045^\circ)\). The flux decreased on a timescale of hours, with an e-fold decay time of 0.6 day. The source was resolved, with the presence of an elongation extending 0.25\'\' between 0.6-1.2 day after the huge X-ray flare. On Sept. 17.93, 22.00 and 24.1 UT, the elongation was at the same position (Hjellming et al. 1999b). They claimed that the proper motion was 0.5\'\' / day, but this is strongly dependent upon the time of the ejection. The jets seem to suggest a high inclination angle. This allowed to classify the source as a new microquasar (for a review on the jet sources see Mirabel & Rodríguez (1999)). An HI absorption experiment towards the source implied a distance \( d > 0.4 \text{kpc} \) (Hjellming et al. 1999a), and these authors proposed a likely distance of 0.5 kpc. 

Orosz et al. (2000b) derived from ESO spectroscopic observations an optical mass function of \( 2.74 \pm 0.12 \, M_\odot \), which, combined with the information on the inclination, makes of V4641 a black hole system with a mass of the compact object \( M_1 \leq 11.70 \, M_\odot \). They also found a spectroscopic period of 2.81678 \pm 0.00056 days, and assuming an extinction \( E(B-V) = 0.32 \pm 0.10 \), quoted a distance between 7.40 and 12.31 kpc (note that this is bigger than previously derived by Orosz et al. (2000c)).

Through our on-going ESO Target of Opportunity program aimed at observing new X-ray flaring sources, we got quickly NIR and optical imaging and spectroscopic observations of this new transient source during its outburst and we could follow it on its decline for a few months (from 1999, September to 2000, June). We report in Section 2 the main observations and results, and discuss them in Section 3. A more detailed study of this source is reported in Chaty et al. (in prep.).  

2. OBSERVATIONS AND RESULTS

The optical imaging and spectroscopic observations took place on 1999, September 16, 17, 28 and 29 and on 2000, March 21 and June, 24; and the infrared imaging and spectroscopic observations on 1999, September 19, 20, 22 and 24, and on 2000, March 20. All the observations took place at ESO, La Silla, but those of June, 24, which were performed at the 1.23 m telescope of the Centro Astronómico Hispano Alemán at Calar-Alto, with the CCD optical camera and exposure times between 30 and 60s (more details on these observations are reported in Martí et al. (2001)). The airmass during the observations was always between 1.008 and 1.020. The optical observations were performed with the NTT telescope and the instrument EMMI RILD. We imaged the source in V, R and I filters, and took some spectra with the grism \#1. The exposure times were nearly 5 min each for the imaging and 15 min for the spectroscopy. The infrared observations were performed with the NTT and the instrument SOFI. The imaging was taken through the filters J, H and Ks, and the spectra with the Grism Red (GR) and 1" slit. The exposure times were chosen as 15 min for the infrared imaging and spectroscopy. The Tables 1 and 2 summarize respectively all the different optical and infrared observations. The lightcurves of the overall optical and infrared observations are respectively reported in Figures 1 and 2. The V-I and J-K colors during the outburst are respectively reported in Figures 3 and 4.  

After the big outburst (from \( V = 14 \) to 8.8 mag), there was still some flaring activity in V, R and I with variations of \( \sim 0.5 \) mag with no significant change in the colors. In NIR there was also some flaring activity with variation of \( \sim 1 \) mag in J and K, with a significant change in the J-K color during the post-outburst (between 2 and 5 days after the giant outburst). This suggests an increased K-contribution compared to J, which can be explained either by the emission of a jet, or the appearance of heated dust (as seen in the case of GRS 1915 + 105 by Mirabel et al. 1999), or even by the interaction with the interstellar medium.

We report the normalized optical spectra offset to get an easier reading in Figure 1. The first striking fact is that on a timescale of one day, the lines were changing from emission to absorption. All the Balmer series is visible: H\( \alpha \), \( \beta \), \( \gamma \), \( \delta \), \( \epsilon \), ... The H\( \alpha \) emission line is extraordinarily strong: one day after the outburst, its equivalent width was \( \sim 100 \, \text{A} \), with a FWZI of \( \sim 6700 \text{ km s}^{-1} \) and a blue wing. There was also a strong He\( I \) 5876\( \text{A} \). The Na-D absorption line equivalent width of 0.45\( \text{A} \) gives \( E(B-V) = 0.25 \) (Alvarez & Zwitter 1977), implying \( N(H) = 0.14 \times 10^{21} \, \text{cm}^{-2} \) (Bohlin et al. 1978). There is a strong variability of the lines: Balmer \( H\alpha \), \( H\beta \) and also of He I. The He II 4680\( \text{A} \) line was claimed to be prominent in emission nearer to the outburst time by Ayani et al. (1999). Since we could not detect it, this line was also very variable. We can also note the blue continuum, visible on the flux calibrated spectra, suggesting the emission from an accretion disk, or from a corona.

In the NIR, the He I and Br\( \gamma \) lines were observed as strong lines by Charles et al. (1999), in a UKIRT/CGS4 spectrum taken on Sept 17.22 UT. He I exhibited an equivalent width of 2.1 nm, and Br\( \gamma \) of 1.4 nm, both showing extended blue wings (FWZI = 5900 km/s), suggesting a high velocity wind component (Charles et al. 1999). The continuum of our NIR spectrum was blue, like the spectrum from Charles et al. (1999). However, our NIR spectrum shows only very faint HeI, He II and Br\( \gamma \) lines, which appear therefore to be strongly variable. The emission lines and the variability suggest the accretion of matter onto a compact object with a high-velocity wind component (\( \sim 6000 \text{ km s}^{-1} \)), also perhaps the presence of a cocoon or a jet.
Table 1. Diary of the optical observations. C.A.: Calar Alto

| Date   | MJD    | Inst | J     | -     | H         | Ks     | J-Ks   |
|--------|--------|------|-------|-------|-----------|--------|--------|
| 19/09/99 | 51441.0 | SOFI | 13.14 ± 0.113 | -     | 13.095 ± 0.04 | 0.045 ± 0.153 |
| 20/09/99 | 51441.98 | SOFI | 12.898 ± 0.026 | -     | 12.809 ± 0.056 | 0.18 ± 0.082 |
| 22/09/99 | 51443.97 | SOFI | 13.927 ± 0.03 | -     | 13.056 ± 0.058 | 0.870 ± 0.088 |
| 24/09/99 | 51445.98 | SOFI | 14.033 ± 0.027 | -     | 13.719 ± 0.029 | 0.314 ± 0.056 |
| 20/03/00 | 51623.42 | SOFI | 12.944 ± 0.007 | 12.849 ± 0.01 | 12.723 ± 0.013 | 0.221 ± 0.02 |

Table 2. Diary of the infrared observations.

3. DISCUSSION

3.1. Nature of the system: the companion star

We plotted on a color-magnitude diagram (CMD, Figure 3) the optical and NIR magnitudes when the source was faint. We plotted in this figure the absolute magnitudes corrected for three different values of the absorption, and corresponding to ten different values of the distance of the source. The values of the absorption correspond to 0.05, 0.1 and 0.15 × 10^{-22} cm^{-2}, derived from our observations and from SAX observations (in’t Zand et al. 2000). The values of the distance of the source go from 1 to 10 kpc. If we constrain the companion object of the binary system to be a main sequence star, its location on the CMD, taking into account the uncertainty on the absorption, suggests that the distance is constrained to 3 < d < 8 kpc. Its spectral type is in this case consistent with an early type B3 - A2 V main sequence star.

However, it is interesting to note that the companion star could be crossing the Hertzsprung gap (U. Kolb, private communication), as for GRO J1655-40 (Kolb et al. 1997), although the mass of the companion star in the case of V4641 Sgr is bigger than for GRO J1655-40. In this view, the location on the CMD would be above the main sequence, the distance of the object could then be still bigger than 3 < d < 8 kpc, this range becoming its minimum distance, and the spectral type would be B3 - A2 IV. In both possibilities the mass is constrained between 2 < M < 10 M☉, suggesting that it is an IMXB or a HMXB. This is consistent with the results derived by Orosz et al. (2000).

3.2. The jets: a new microquasar?

If the elongation seen in the radio was a moving component, the proper motion was between 224 < μ < 788 mas/d depending on the exact time of the ejection. For the sake of discussion, we will assume that this is the approaching (brighter) condensation with μ_a = 500 mas/d. Since D ≥ \mu, and from our results D ≥ 3 kpc, we conclude that the apparent velocity in the plane of the sky would be strongly superluminal, v_c greater than 8c at the distance of 3 kpc. However, no movement of this elongation was detected between Sept. 16.02 and 24.1. This suggests an interaction with surroundings at 0.25″ ≥ 1.5 × 10^3 AU at the distance of 6 kpc. This is possible if the ejections began to take place at least 10 days before the radio detection e.g. on September, 8th, and we can see from Figure 3 that the source was already active in the optical at this date.

It seems therefore that the activity of this source was not as sporadic as we could have thought at the beginning. Indeed, a previous optical outburst occurred in 1999, August (Watanabe 1999), and RXTE could detect this source during 270 days before the giant outburst (in’t Zand; Markwardt, these proceedings). Furthermore, during 5 days before the giant outburst, the source was in the optical continuously 2 magnitudes brighter than immediately after, showing a modulation at the orbital period, with no X-ray emission (typical upper limit of 12 mCrab, in’t Zand et al. 2000). All these facts, combined to the high X-ray variability, show that, although the Orosz results suggest that the accretion in the system is of Roche-lobe overflow type, it could exist in addition a mass loss from the vicinity of the compact object. At a distance of 6 kpc, the maximum luminosity of the source is ∼ 4 × 10^{38} erg s^{-1}, therefore close to the Eddington limit of a ∼ 10 M☉ object (1.3 × 10^{39} erg s^{-1}). If the transfer rate is highly super-Eddington such a wind could arise. This wind could be the reason...
why surrounding matter was present, allowing the interaction between further ejections and surrounding matter to take place. In this case, the companion star is more likely to be a main sequence star (U. Kolb, private communication).

Finally, it is interesting to note that Martí et al. (2001) observed this source to look for minute to hour variability, discovering a 0.1 mag variability on the time scale of hours. Among the different interpretations considered by them, it is suggested that this variability could originate in an extended corona surrounding the jets, by analogy with SS 433. If this interaction between the jets and the surrounding medium is confirmed, this source could therefore be added to the short list of microquasars where such an interaction has been detected (see e.g. Mirabel & Rodríguez (1999) & Chaty et al. (2001)).

4. CONCLUSIONS

From our optical and the SAX observations we constrained $0.05 < N(H) < 0.15 \times 10^{22}$ cm$^{-2}$. From our optical and NIR colors the distance is $3 < D < 8$ kpc, and the companion star would be a main sequence star of spectral type B3 - A2 V. If the source is crossing the Hertzsprung gap, this determination of the distance would become its minimum distance, and the spectral type of the companion star would be B3 - A2 IV. The system is therefore an IMXB or a HMXB. From the radio images, the NIR colors, and the optical spectra, there is a strong suggestion of interaction of the ejecta of the source with its surroundings. This surrounding matter could have originated from a wind created by fluctuations around the central object, and in this case the companion star would more certainly be a main sequence star. Further observations would be useful to confirm this existence of surrounding matter.

ACKNOWLEDGEMENTS

S.C. thanks Rob Hynes for poiting out this new flaring source on September 1999, Bob Hjellming for all the spontaneous communications he gave on the radio observations of this source, and Ulrich Kolb for many stimulating discussions and careful rereading of the manuscript. S.C. is very grateful to the ESO staff for their availability and skills to perform service observations for override programs, and in particular to the NTT team: Leonardo Vanzi, Olivier Hainaut, Stéphane Brillant and Vanessa Doublier. S.C. acknowledges support from grant F/00-180/A from the Leverhulme Trust. IFM acknowledges partial support from Conicet/Argentina. JM acknowledges partial support from DGICYT (PB97-0903) and Junta de Andalucía (Spain).

REFERENCES

Ayani K., Peiris T.C., Clarke Institute C., Sep. 1999, IAU Circ., 7254, 1+
Bohlin R.C., Savage B.D., Drake J.F., Aug. 1978, Astrophys. J., 224, 132
Charles P.A., Shahbaz T., Geballe T., Oct. 1999, IAU Circ., 7267, 2+
Chaty S., Rodríguez L.F., Mirabel I.F., et al., 2001, Astron. Astrophys., 366, 1041
Hjellming R.M., Rupen M.P., Mioduszewski A.J., Sep. 1999a, IAU Circ., 7254, 2+
Hjellming R.M., Rupen M.P., Mioduszewski A.J., Sep. 1999b, IAU Circ., 7265, 2+
Hjellming R.M., Rupen M.P., Hunstead R.W., et al., Dec. 2000, Astrophys. J., 544, 977
in’t Zand J., Heise J., Bazzano A., et al., 1999, IAU Circ., 7119
in’t Zand J.J.M., Kuulkers E., Bazzano A., et al., May 2000, Astron. Astrophys., 357, 520
Kato T., Uemura M., Stubbings R., Watanabe T., Monard B., Oct. 1999, Informational Bulletin on Variable Stars, 4777, 1+
Kazarovets E.V., Samus N.N., Durlevich O.V., Mar. 2000, Informational Bulletin on Variable Stars, 4870, 1+
Kolb U., King A., Ritter H., Frank J., 1997, Astrophys. J., 485, L33
Markwardt C., Swank J., Marshall F., 1999, IAU Circ., 7120
Martí J., Zamanov R., Paredes J.M., Ribó M., 2001, Informational Bulletin on Variable Stars, submitted
Mirabel I., Rodríguez L., 1999, Annu. Rev. Astron. Astrophys., 37, 409
Mirabel I.F., Rodríguez L.F., Chaty S., et al., 1996, Astrophys. J., 472, L111
Munari U., Zwitter T., Feb. 1997, Astron. Astrophys., 318, 269
Orosz J.A., Kuulkers E., van der Klis M., et al., Jun. 2000a, IAU Circ., 7440, 1+
Orosz J.A., Kuulkers E., van der Klis M., et al., Dec. 2000b, In: American Astronomical Society Meeting, vol. 197, 8320+
Ruelas-Mayorga R.A., Apr. 1991, Revista Mexicana de Astronomía y Astrofísica, 22, 27
Samus N.N., Hazen M., Williams D., et al., Oct. 1999, IAU Circ., 7277, 1+
Smith D., Levine A., Morgan E., 1999, IAU Circ., 7253
Stubbings R., 1999, IAU Circ., 7253
Watanabe T., 1999, VSOLJ Variable Star Bulletin, 34, 3
Wijnands R., van der Klis M., Jan. 2000, Astrophys. J., 528, L93
Williams G.V., Sep. 1999, IAU Circ., 7253, 3+

Figure 1. Optical Observations. +: VSNET, △: B, ×: V, ∗: R, ○: I magnitudes. The beginning of the optical activity took place on 1999 Sept. 8 UT (= MJD 51429.5), followed by the outburst of 1999 Sept. 15.7 UT (= MJD 51437).

Figure 2. NIR (+ optical) observations. +: VSNET, ×: V, ∗: J, ▷: H, ○: Ks magnitudes.

Figure 3. Top: +: VSNET, ×: V, △: I magnitudes. Bottom: V-I color.

Figure 4. Top: +: VSNET, ×: V, ∗: J, ○: Ks magnitudes. Bottom: J-Ks color.

Figure 5. Normalized and offset optical spectra.

Figure 6. Color-magnitude [V-Ks, Ks] diagram. *: Min magnitudes of V4641 Sgr. +: typical main sequence stars (Ruelas-Mayorga 1991). 0.28, 0.56 and 0.84 are the visual absorptions corresponding respectively to the column densities $0.05, 0.1$ and $0.15 \times 10^{22} \text{ cm}^{-2}$. 