Misalignment of the microquasar V4641 Sgr (SAX J1819.3–2525)

Rebecca G. Martin,* Rubens C. Reis and J. E. Pringle

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

Accepted 2008 August 8. Received 2008 August 7; in original form 2008 July 19

ABSTRACT

In the microquasar V4641 Sgr, the spin of the black hole is thought to be misaligned with the binary orbital axis. The accretion disc aligns with the black hole spin by the Lense-Thirring effect near to the black hole and further out becomes aligned with the binary orbital axis. The inclination of the radio jets and the Fe Kα line profile have both been used to determine the inclination of the inner accretion disc but the measurements are inconsistent. Using a steady-state analytical-warped disc model for V4641 Sgr, we find that the inner disc region is flat and aligned with the black hole up to about 900Rg. Thus, if both the radio jet and fluorescent emission originate in the same inner region then the measurements of the inner disc inclination should be the same.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: V4641 Sgr.

1 INTRODUCTION

Microquasars are binary systems in which material is accreted from a normal star on to a compact object. They differ from typical X-ray binaries by the strong presence of a persistent or episodic radio jet (Mirabel & Rodríguez 1999). The compact object is usually associated with a neutron star or a stellar mass black hole. To date, there are over 15 microquasars for which the compact object has been dynamically confirmed to be a stellar mass black hole (Orosz 2003). However, only four of these systems have well-resolved relativistic radio jets (XTE J1550–564, GRO J1655–40, GRS 1915+105 and V4641 Sgr, Garcia et al. 2003).

It is usually assumed that the inclination of the jet axis is perpendicular to the orbital plane of the binary. However, it has been shown by Maccarone (2002) and more recently by Martin, Tout & Pringle (2008) that the alignment time-scale in microquasars is usually a significant fraction of the lifetime of the system. If the black hole in such microquasars were formed with misaligned angular momentum, as expected from supernova-induced kicks, then it would be likely that the system would remain misaligned for most of its lifetime.

Precise measurements of both the orbital plane and jet inclination are known for two systems. GRO J1655–40 is a microquasar thought to contain a rapidly rotating black hole (Zhang, Cui & Chen 1997; Reis et al., in preparation) with a mass constrained to be larger than 6.0 M⊙ (Orosz & Bailyn 1997). Hjellming & Rupen (1995) measured a jet inclination of 85° ± 2° to the line of sight and it is thus misaligned by at least 10° to the orbital plane, with an inclination of 70.2° ± 1.9° (Greene, Bailyn & Orosz 2001). Martin et al. (2008) presented a detailed investigation of the alignment time-scale of this system and found that it is consistent with the lifetime of the secondary star.

V4641 Sgr was discovered as an X-ray source independently with the Wide Field Cameras on BeppoSAX on 1999 February 20 (in’t Zand et al. 1999) and with the Proportional Counter Array on the Rossi X-ray Timing Explorer (RXTE) on 1999 February 18 (Markwardt, Swank & Marshall 1999). Spectroscopic observations made between 1999 September 17 and 1999 October 16 led to a mass function f(M) = 2.74 ± 0.12 M⊙ (Orosz et al. 2001). From the lack of X-ray eclipses, combined with the large amplitude of the folded light curve, they deduced an orbital inclination angle in the range 60° ≤ iorb ≤ 70.7 and mass 8.73 ≤ M∗ BH ≤ 11.70 M⊙ for the compact object. Radio observations of V4641 Sgr (Hjellming et al. 2000) made during the 1999 September outburst found the jet expanding at apparent superluminal velocities with a proper motion ranging between 0.22 and 1 arcsec per day. Based on the radio information, Orosz et al. (2001) suggested that the jet must be highly beamed and have an inclination along the line of sight of ijet ≤ 10°. This differs significantly from the inclination of the binary orbital axis.

X-ray spectral analysis made on BeppoSAX observations of V4641 Sgr (in’t Zand et al. 2000) revealed the presence of a strong Fe Kα emission with an equivalent width between 0.3 and 1 keV. They interpreted this as fluorescent emission using a photoionized medium. The presence of this Fe fluorescent emission was later confirmed by Revnivtsev et al. (2002) from a collection of RXTE data. They found an emission line at about 6.6 keV with an equivalent width of about 360 eV. A more recent analysis of the source with RXTE data obtained during the outburst of 2003 August 5–17 (Maitra & Bailyn 2006) showed the presence of both a strong Fe Kα fluorescent emission line near 6.5 keV and a characteristic Compton hump at about 20 keV. If these features are attributed to the reprocessing of a hard X-ray (power-law) continuum by cold
matter in an accretion disc (Reynolds & Nowak 2003; Reynolds & Fabian 2008) then the degree of broadening observed implies that the emitting region is very close to the black hole. The shape of the line profile can then give an indication of both the radius of the emitting material from the black hole as well as the inclination of the inner accretion disc (Fabian et al. 1989; Laor 1991). In this way, Miller et al. (2002) obtained an estimate for the inclination of the innermost part of the accretion disc of 43° ± 15° (90 per cent confidence).

2 MISALIGNMENT IN V4641 SGR

The orbit of V4641 Sgr is thought to be misaligned with the axis of the jet by about 60°. The black hole was formed from a supernova, which probably gave a kick to the black hole. Even a small velocity kick can lead to a large misalignment between the spin axis of the black hole and the binary orbital axis (Brandt & Zdziarski 2001).

The intermediate inclination angle found from the Fe Kα line profile prompted the suggestion of a hierarchy of inclinations (Butt, Maccarone & Prantzos 2003) with $i_{\text{interdisc}} = 43° ± 15°$, which is greater than $i_{\text{jet}}$ ≤ 10°. The Blandford & Znajek (1977) mechanism for jet formation uses the rotational energy of a rapidly spinning black hole. Relativistic jets are formed in the inner parts of the accretion disc at around 6$R_g$ (Nishikawa et al. 2005) and so must be perpendicular to the inner disc. The gravitational radius is defined as

$$R_g = \frac{GM_{\text{BH}}}{c^2} = 1.54 \times 10^6 \frac{M_{\text{BH}}}{10.4 M_\odot} \text{ cm.} \quad (1)$$

Unless the mechanism for jet formation is very different, we expect that the jet formation region of the inner disc is at an inclination of less than 10°.

This is hard to reconcile even with the huge uncertainties in the measurement of the inclination of the inner disc from the profile of the Fe Kα line (Miller et al. 2002). The inclinations as measured by these two independent techniques, the Fe Kα and radio jets, are found to differ by at least 43° − 15° − 10° = 18° if we take the lower limit for the inner disc inclination.

3 WARPED DISC MODEL

A warp in an accretion disc around a spinning black hole is driven by Lense-Thirring precession. Evidence for this effect, that leads to a warped accretion disc, can be seen in NGC 4258 where the disc can be observed by maser emission (Martin 2008). However, in the case of V4641 Sgr, we cannot observe the disc directly. The inner parts of the disc align with the black hole by the Bardeen & Petterson (1975) effect and the outer parts are aligned with the binary orbit because of the angular momentum with which they accrete as well as tidal effects. Scheuer & Feiler (1996) found a steady-state solution for the inclination of a disc warped by the Bardeen–Petterson effect by solving the disc equations of Pringle (1992) for a disc of constant surface density. Martin, Pringle & Tout (2007) generalized this to a power-law density distribution. We note that it is possible to have a microquasar which is still misaligned (e.g. GRO J1655−40, Martin et al. 2008) and so we do not need to go into the details of the stellar evolution here for this system.

The luminosity of the source is

$$L = 6 \times 10^{-3} L_{\text{edd}} = 7.5 \times 10^{35} \left( \frac{M_{\text{BH}}}{M_\odot} \right) \text{ erg s}^{-1}, \quad (2)$$

(Miller et al. 2002) where $L_{\text{edd}}$ is the Eddington Luminosity and so we find $L = 7.8 \times 10^{36} \text{ erg s}^{-1}$ with $M_{\text{BH}} = 10.4 M_\odot$. The accretion rate is

$$M = \frac{L}{\epsilon c^2} = 1.38 \times 10^{-9} M_\odot \text{ yr}^{-1}, \quad (3)$$

where we take the accretion efficiency $\epsilon = 0.1$. We use a steady-state disc model with surface density $\Sigma \propto R^{-3/4}$ (Shakura & Sunyaev 1973), where $R$ is the radius in the disc. This is the outermost region (c) of the Shakura & Sunyaev disc. The middle region (b) has $\Sigma \propto R^{-3/2}$ and the steady-state shape of this disc would almost be identical to that of a disc in region (c) (Martin et al. 2007). The transition radius from region (b) to (c) is at $R_{\text{t}} = 960 R_g$. Note that we have a different definition of $R_g$ to Shakura & Sunyaev (1973). The innermost region (a) of the Shakura & Sunyaev disc has $\Sigma \propto R^{3/2}$ but the transition radius does not exist here and so the disc in V4641 Sgr has only regions (b) and (c). We also take $v_1$ and $v_2 \propto R^{3/4}$ (Wijers & Pringle 1999) as used by Martin et al. (2007), where $v_1$ is the viscosity corresponding to the azimuthal shear and $v_2$ to the vertical shear.

Martin et al. (2008) find the radius up to which the Lense-Thirring effect dominates the viscous effects in the disc to be

$$R_{\text{warp}} = 1.40 \times 10^8 \left( \frac{a}{0.7} \right)^{4/7} \left( \frac{\alpha_2}{2} \right)^{-16/35} \left( \frac{M_{\text{BH}}}{10.4 M_\odot} \right)^{9/7} \frac{\dot{M}}{1.38 \times 10^{-9} M_\odot \text{ yr}^{-1}} \text{ cm,} \quad (4)$$

where $a$ is the dimensionless spin of the black hole and $\alpha_2$ is the dimensionless viscosity parameter associated with the vertical shear in the disc. For stellar mass black holes, there are only a few sources with determined spins which vary from about 0.4 to that of a maximally rotating black hole (McClintock, Narayan & Shafee 2007; Miller et al. 2008; Reis et al. 2008). We choose $a = 0.7$ in the middle of this range. The ratio of the warp radius to the gravitational radius of the disc is

$$\frac{R_{\text{warp}}}{R_g} = 912 \left( \frac{a}{0.7} \right)^{4/7} \left( \frac{\alpha_2}{2} \right)^{-16/35} \left( \frac{M_{\text{BH}}}{10.4 M_\odot} \right)^{2/7} \frac{\dot{M}}{1.38 \times 10^{-9} M_\odot \text{ yr}^{-1}} \text{ cm.} \quad (5)$$

We note that this radius is far from the inner edge of the disc as defined by the innermost stable circular orbit.

The direction of the angular momentum of a disc annulus is given by $I = (I_x, I_y, I_z)$ with $|I| = 1$. We let $W = I_x + i I_y$, where $i = \sqrt{-1}$, and find the warped disc profile for this model to be

$$W = \frac{2 \sin(i_{\text{obs}} - i_{\text{jet}}) - i_{\text{jet}}^{1/2}}{\Gamma(2/7)(7/4)^{2/7}} \left( \frac{R_{\text{warp}}}{R} \right)^{1/4} \times K_{2/7} \left[ \frac{4\sqrt{2}}{7} (1 - i) \left( \frac{R}{R_{\text{warp}}} \right)^{-2} \right] \quad (6)$$

(Martin et al. 2007) in the frame of the black hole. The inclination of the disc at radius $R$ is

$$\theta(R) = \cos^{-1}(i) = \cos^{-1} \left( \sqrt{1 - |W(R)|^2} \right). \quad (7)$$

In Fig. 1, we plot the inclination of the disc in the frame of the black hole in V4641 Sgr. We see that the disc is flat and aligned with the black hole out to a radius of about $R_{\text{warp}}$, which in the case of V4641 Sgr is about 900 $R_g$ (equation 5). The region where the Fe Kα line is emitted is likely to be within the innermost 20 $R_g$ (Fabian 2006) so the inclination measured by the Fe Kα method (Miller et al. 2002)
Figure 1. The inclination in the frame of the black hole of a steady-state accretion disc warped by the Lense-Thirring effect with Σ ∝ R^{-3/4} and v_1, v_2 ∝ R^{3/4} which has a misalignment of 60° between the jet and the binary orbital axis.

should be the same as that of the innermost part of the accretion disc and should thus be the same as the inclination of the radio jets which are formed up to around 6 R_g.

4 DISCUSSION

In view of the discrepancy between the measured inclination angles of the innermost parts of the accretion disc by Fe Kα profile fitting and that of the radio jet, Butt et al. (2003) suggested a hierarchical system of inclinations of the jet, inner disc and binary orbit. We have shown here that if both the jet and iron fluorescent emission originate within about 900 R_g then their measured inclination should be the same. This implies that either the measured value from the jet, Fe Kα or both are inaccurate. It was suggested by Chaty et al. (2001) and later by Narayan & McClintock (2005) that the inclination of the radio jet could, in fact, be as high as that of the orbital inclination. This uncertainty comes about because the precise time of the radio outburst is still unknown. However, the general consensus is that the radio outbursts started at the same time as those of the X-ray and thus we get the limit on the inclination of the jet of less than 10°.

The iron emission line seen at 6.5 keV has been generally interpreted as that originating from a cold accretion disc. In this way, Miller et al. (2002) obtained an inclination of about 43°. However, Maitra & Bailyn (2006) have argued that the emission could originate in a varying, optically thick cloud enshrouding the black hole. The strong broadening of the line would thus be attributed to the highly dynamical environment and outflows. If this interpretation is correct then the inclination as measured by Miller et al. (2002) is irrelevant.

We found that the warp radius in V4641 Sgr is around 900 R_g for a black hole with moderate spin and the accretion disc is aligned with the black hole almost up to this radius. Given the similarity between the evolutionary state of this system and GRO J1655−40, we expect the spin of the black hole to be large. Even if the spin of the black hole is as low as a = 0.2 and the accretion rate is as high as the Eddington accretion rate, we find that R_{warp} = 184 R_g and the disc would still be essentially flat in this region. If the jet is emitted within this radius, as is generally believed, then we would expect an agreement between the inclination of the jet and that of the inner disc as obtained from the iron line profile. However, it is possible that the warp radius is very much closer to the black hole in the unlikely event that the spin of the black hole, a, is very small. In that case, different values for the inclination of the warped inner disc could be expected.

5 CONCLUSIONS

We find that, in the accretion disc in V4641 Sgr, the region thought to be both the origin of the jets and the emission site of the Fe Kα line is flat and aligned with the central black hole. Thus, we would expect the inclinations measured for the jets and with the Fe Kα line to be similar. Because there is a significant difference between the two measurements we conclude that one or both of them must be inaccurate or our model incorrect. It is important that this system be observed in more detail to resolve this in the near future.

ACKNOWLEDGMENTS

RGM and RCR thank STFC for financial support.

REFERENCES

Bardeen J. M., Petterson J. A., 1975, ApJ, 195, L65
Blandford R. D., Znajek Z., 1977, MNARS, 170, 433
Brandt N., Podsiadlowski P., 1995, MNARS, 274, 461
Butt Y. M., Maccarone T. J., Prantzos N., 2003, ApJ, 587, 748
Chaty S., Mirabel I. F., Marti J., Rodríguez L. F., 2001, ApSS, 276, 153
Fabian A. C., 2006, Astron. Nachr., 327, 943
Fabian A. C., Rees M. J., Stella L., White N. E., 1989, MNARS, 238, 729
Garcia M. R., Miller J. M., McClintock J. E., King A. R., Orosz J., 2003, ApJ, 591, 388
Greene J., Bailyn C. D., Orosz J. A., 2001, ApJ, 554, 1290
Hjellming R. M., Rutep M. P., 1995, Nat, 375, 464
Hjellming R. M. et al., 2000, ApJ, 544, 977
in’t Zand J. J. M., Heise J., Bazzano A., Cocchi M., di Ciolo L., Muller J. M., 1999, IAUC, 7119, 1
in’t Zand J. J. M. et al., 2000, A&A, 357, 520
Laor A., 1991, ApJ, 376, 90
Maccarone T. J., 2002, MNARS, 336, 1371
McClintock J. E., Narayan R., Shafee R., 2007, preprint (arxiv:0707.492v1)
Maitra D., Bailyn C. D., 2006, ApJ, 637, 992
Markwardt C. B., Swank J. E., Marshall F. E., 1999, IAUC, 7120, 1
Martin R. G., 2008, MNARS, 387, 830
Martin R. G., Pringle J. E., Tout C. A., 2007, MNARS, 381, 1617
Miller J. M., 2008, MNARS, 387, 188
Miller J. M., Fabian A. C., in’t Zand J. J. M., Reynolds C. S., Wijnands R., Nowak M. A., Lewin W. H. G., 2002, ApJ, 577, L15
Miller J. M. et al., 2008, ApJ, 679, L113
Mirabel I. F., Rodríguez L. F., 1999, ARA&A, 37, 409
Narayan R., McClintock J. E., 2005, ApJ, 623, 1017
Nishikawa K.-I., Richardson G., Koide S., Shibata K., Kudoh T., Hardee P., Fishmas G. J., 2005, ApJ, 625, 60
Orosz J. A., 2003, van der Mucht K., Herrero A., Cesar E., eds, IAU Symp. 212, A massive star odyssey: from main sequence to supernova. Astron. Soc. PAS., San Francisco, p. 365
Orosz J. A., Bailyn C. D., 1997, ApJ, 477, 876
Orosz J. A. et al., 2001, ApJ, 555, 489
Pringle J. E., 1992, MNRAS, 258, 811
Reis R. C., Fabian A. C., Ross R. R., Miniutti G., Miller J. M., Reynolds C., 2008, MNRAS, 387, 1489
Revnivtsev M., Gilfanov M., Churazov E., Sunyaev R., 2002, A&A, 391, 1013
Reynolds C. S., Nowak M. A., 2003, Phys. Rev., 377, 389
Reynolds C. S., Fabian A. C., 2008, ApJ, 675, 1048
Scheuer P. A. G., Feiler R., 1996, MNRAS, 282, 291
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Wijers R. A. M. J., Pringle J. E., 1999, MNRAS, 308, 207
Zhang S. N., Cui W., Chen W., 1997, ApJ, 482, 155

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.