Mem. S.A.It. Vol. 82, 82

Memorie della

The puzzling varying radio structure of LS I +61°303

L. Zimmermann and M. Massi

Max-Planck-Institut fuer Radioastronomie, Auf dem Huegel 69, 53121 Bonn
e-mail: `lzimmerm@mpifr-bonn.mpg.de`

Abstract. Recent analysis of the radio spectral index and high energy observations have shown that the two-peak accretion/ejection microquasar model applies for LS I +61°303. Aim of this work is therefore, to find in the context of the microquasar scenario a possible explanation for the fast (daily) variations of the position angle observed with MERLIN and confirmed by consecutive VLBA images. We calculate what could be the precessional period for the accretion disk under tidal forces of the Be star (P_{TF}) or under the effect of frame dragging produced by rotation of the compact object (P_{LT}). Our results are that P_{TF} is at least one year, while P_{LT} strongly depends on the truncated radius of the accretion disk (R_{tr}). We determine $R_{tr} = 300r_g$ for observed QPO at 2 Hz. This value is much above the few r_g, where the Bardeen-Petterson effect should align the midplane of the disk, and agrees well with the expectation of the truncated radius for the very low/hard state of LS I +61°303 ($> 100r_g$). For $R_{tr} = 300r_g$, P_{LT} results in a few days for a slow rotator. Therefore we conclude that Lense-Thirring precession could explain the daily variations of the ejecta angle observed in LS I +61°303.

Key words. Black hole physics – Radio continuum: stars – X-rays: binaries – X-rays: indiviual (LS I +61°303)

1. Introduction

LS I +61°303 is an X-ray binary formed by a compact object and a massive star with an optical spectrum typical for a rapidly rotating B0 V star (Hutchings & Crampton 1981). The system is a strong periodic radio and gamma-ray emitter. Radio spectral index analysis by Massi & Kaufman Bernadó (2009) have found two peaks along the orbit of LS I +61°303. Each peak shows the microquasar characteristic of a switch from a steady (optically thick) to a transient (optically thin) jet. Moreover, also high energy observations with EGRET (Massi et al. 2005) and Fermi-LAT (Abdo et al. 2009) indicate two peaks (see discussion in Massi & Zimmermann (2010) and Massi in this volume). It has been shown from theory that for a microquasar with an eccentric orbit (LS I +61°303: e=0.54-0.7 (Aragona et al. 2009; Casares et al. 2005)), indeed, the different relationship between the accretion rate for density and velocity described by Bondi (1952), creates two peaks in the accretion rate curve, one at periastron and a second one towards apastron (Taylor et al. 1992; Bosch-Ramon et al. 2006). In the next section we will discuss the puzzling behaviour of the associ-

Send offprint requests to: L. Zimmermann ated ejection, when shown at high radio resolution.

2. Puzzling precession

When comparing VLBI maps of LS I +61°303 from Taylor et al. (2000) with VLBA maps from Dhawan et al. (2006) (see Fig. 1), it is obvious that the observed jet has different position angles in the two images. When closely inspecting a sequence of images by Dhawan et al. (2006), taken three days apart, in Fig. 2, it becomes clear that at some epochs the receding jet appears attenuated while at others it is not visible at all. Dhawan et al. (2006) measured in their VLBA images a rotation of the inner structure of roughly $5° - 7°$ in 2.5 hrs, which is almost 60°/day. The variations of LS I +61°303 are therefore of a short timescale. Two MERLIN images of LS I +61°303 , taken one day apart, revealed in fact the same variation of 60° in position angle in only one day (Massi et al. 2004) as can be seen in Fig. 2.

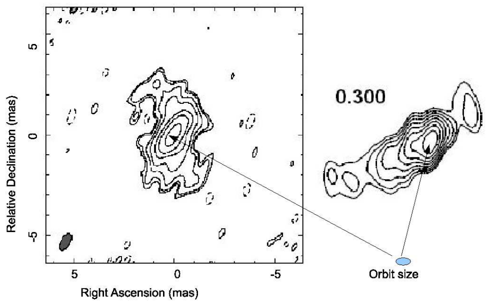

Fig. 1. The left picture shows a VLBI image of LSI +61303 from 2000 (Taylor et al. 2000), the right picture shows a VLBA image from 2006 (Dhawan et al. 2006). When comparing the pictures, it is obvious that the position angle is different.

Precession of the accretion disk (and therefore of the jet), causing the jet to point closer to or farther away from the line of sight, would explain the observed variations in the position

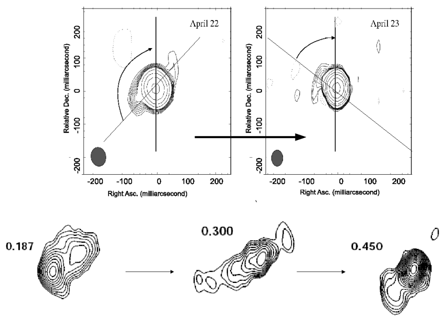

Fig. 2. Upper two panels: Two 24h MERLIN images from LS I +61°303, taken on April 22nd and 23rd in 2004 (Massi et al. 2004). Lower panels: Three consecutive VLBA images from LS I +61°303, taken three days apart from each other (the orbital phase is noted) in 2006 (Dhawan et al. 2006).

angle and flux. The most likely cause for precession of an accretion disk of a compact object is an assymetric supernova explosion of the progenitor, resulting in a tilt of the compact object (Fragile et al. 2007). Then, either the accretion disk is coplanar with the compact object, and therefore subject to the gravitational torque of the Be star, or instead, the accretion disk is coplanar with the orbit, but tilted in respect to the compact object, which induces Lense-Thirring precession, if the compact object rotates.

2.1. Tidally forced precession

If the accretion disk is tilted with respect to the binary orbital plane, then its precession can be tidally induced by the companion star. The tidal forces acting upon an accretion disk can be formulated using linear perturbation theory (Larwood 1998; Massi & Zimmermann 2010):

$$P_{\rm TF} = \frac{61.8}{\cos\delta}\frac{(1+\mu)^{1/2}}{\mu}\left[\frac{0.6+\mu^{2/3} ln(1+\mu^{-1/3})}{0.49\frac{1.4}{1+[ln(1.8\mu)]^{0.24}}}\right]^{3/2} \qquad (1)$$

In Fig. 3, P_{TF} is analysed with respect to the mass ratio, μ, and the inclination angle, δ, for LS I +61°303, yielding a precessional period above 460 d for the possible values. In addition, Fig. 4 shows the dependence on the disk size (Eq. 1 in Massi & Zimmermann (2010)).

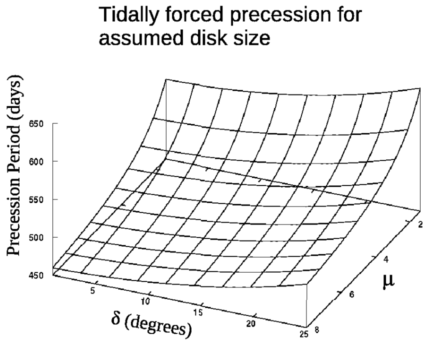

Fig. 3. Precession period due to a tidal torque induced by the Be star as a function of the mass ratio, μ, and the inclination angle, δ, of the orbital plane with respect to the plane of the disk (Eq. 1) (Massi & Zimmermann 2010). Even for the smallest possible values of δ and the highest values of μ for LS I +61°303, we already get $P_{\rm prec}$= 460 d.

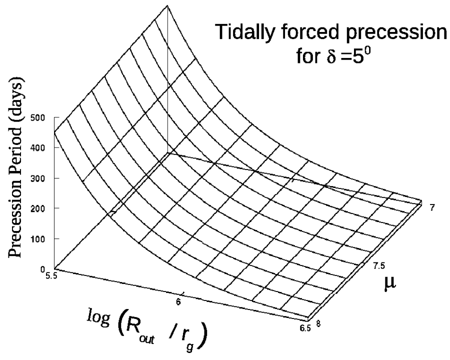

Fig. 4. Precession period due to a tidal torque induced by the Be star as function of the mass ratio, μ, and the disk size $\frac{R_{out}}{r_g}$ for an inclination angle of $\delta = 5^{\rm deg}$ (Massi & Zimmermann 2010). One needs to enlarge the disk size one order of magnitude, reaching the value of $\frac{R_{out}}{r_g} = 10^{6.5}$, to finally reduce P_{TF} to a few days. Such a large R_{out} value is unlikely. Already beyond about 10^4 gravitational radii, self-gravitation is larger than central gravitation, and the disk becomes gravitationally unstable (Collin & Huré 1999).

From this analysis the tidal force model cannot reproduce the precessional period observed in LS I +61°303.

2.2. Lense-Thirring precession

Lense-Thirring, also called frame-dragging, is an effect that concludes from general relativity, and which was first predicted in 1918 (Lense & Thirring 1918). According to theory, tilted orbits around a rotating object experience a torque, which causes the plane of the orbit to precess. Therefore when a spinning compact object has a misaligned accretion disk, precession of the disk will arise via the Lense-Thirring effect. The precessional period in days for a test particle inferred by the Lense-Thirring effect can be written as (Caproni et al. 2006; Wilkins 1972; Stella & Vietri 1998):

$$P_{\rm LT} = \frac{1.8{\times}10^{-10}}{a_*}\frac{M_{\rm compact\,object}}{M_\odot}\left(\frac{r}{r_g}\right)^3, \quad (2)$$

where r is the radial distance of the test particle to the compact object and a_* the dimensionless spin parameter, such that the angular momentum J is $J = \frac{a_* G M^2_{\rm compact\,object}}{c}$ (Fragile et al. 2001). The truncated radius, R_{tr}, of the geometrically thin accretion disk in the low/hard state can be used for the radial distance r. For LS I +61°303, it can be estimated from QPO, observed in LS I +61°303 at a time where the system is in the same X-ray state as for the observed variations in the position angle (see discussion in Massi & Zimmermann (2010)). In 2008, during their monitoring with RXTE (2-10 keV), Ray & Hartman observed a period of strong variability with a spectrum, best fitted by a powerlaw of photon index about 1.5, which indicates that the source was in the low/hard state. A power spectral analysis revealed QPO with a frequency of 2 Hz. Setting this equal to the relativistic Keplerian frequency, ν_K, and following Caproni et al. (2006), this yields a truncated radius of $\frac{R_{tr}}{r_g}$ = 300 (this value lies well above the limit of a few r_g, where the Bardeen-Patterson effect would cause an alignment of the disk with the rotation axis of the compact object (Nelson & Papaloizou 2000)). This value is then used to calculate the precession period for Lense-Thirring. The results from this analysis are depicted in Fig. 5 and 6. If the compact ob-

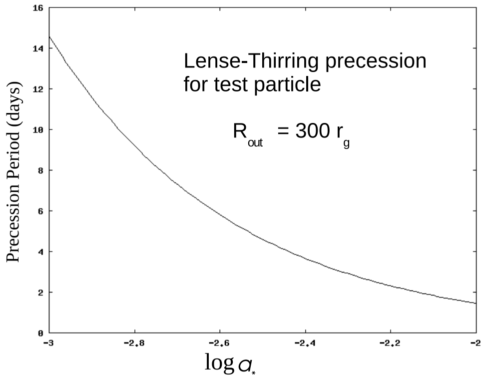

Fig. 5. Lense-Thirring precession period for a test particle as a function of the dimensionless specific angular momentum, a_*, (Eq. 2). The orbit of R_{tr} = $300r_g$ has been determined by observed QPO at 2 Hz (Ray & Hartman 2008) during the low/hard state (Massi & Zimmermann 2010).

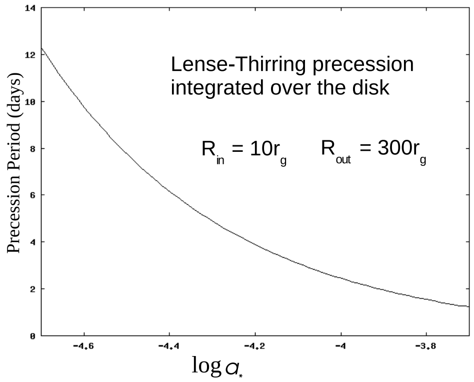

Fig. 6. Lense-Thirring precession period for a geometrically thick accretion flow with inner and outer radii r_i and R_{tr} (Massi & Zimmermann 2010).

ject is a slow enough rotator with $0.001 < a_* < 0.01$, a precessional period of a few days for the Lense-Thirring precession can be deduced, which corresponds to what is seen in the MERLIN and VLBA observations.

3. Conclusions

Two consecutive MERLIN observations of LS I +61°303 showed a rotation of the position angle of the radio structure of $\simeq 60°$ in only 24 hours (Massi et al. 2004). Several consecutive VLBA images by Dhawan et al. (2006), three days apart, have confirmed the fast variations. Here, we analyse precession due to the tidal torque induced by the Be star and to the Lense-Thirring precession induced by the tilted rotating compact object. It is unlikely that the observed *days* time scale could be created by tidal precession. It is shown that this mechanism would produce too large a precessional period of $P_{\rm prec} \geq 460$d. To lower the precessional period to a few days one should increase the disk size above the limit of any stable disk. On the contrary, for Lense-Thirring precession we determine that a slow rotator induces a $P_{\rm prec}$ of a few days for a truncated inner radius of $300\,r_g$, consistent with the QPO at 2 Hz observed by Ray & Hartman (2008).

Acknowledgements. The work of L. Zimmermann is partly supported by the German Excellence Initiative via the Bonn Cologne Graduate School.

References

Aragona, C., McSwain, M. V., Grundstrom, E. D., Marsh, A. N., Roettenbacher, R. M., Hessler, K. M., Boyajian, T. S., & Ray, P. S. 2009, ApJ, 698, 514
Abdo, A. A., et al. 2009, ApJ, 701, L123
Bondi, H. 1952, MNRAS, 112, 195B
Bosch-Ramon, V., Paredes, J. M., Romero, G. E., & Ribó, M. 2006, A&A, 459, L25
Casares, J., Ribas, I., Paredes, J. M., Martí, J., & Allende Prieto, C. 2005, MNRAS, 360, 1105
Collin, S., Huré, J.-M., 1999, A&A, 341, 385398
Caproni, A., Livio, M., Abraham, Z., & Mosquera Cuesta, H. J. 2006, ApJ, 653, 112
Dhawan, V., Mioduszewski, A., & Rupen, M. 2006, Proceedings of the VI Microquasar Workshop, p. 52.1
Fragile, P. C., Mathews, G. J., & Wilson, J. R. 2001, ApJ, 553, 955
Fragile, P. C., Blaes, O. M., Anninos, P., & Salmonson, J. D. 2007, ApJ, 668, 417
Hutchings, J. B., Crampton, D. 1981, PASP, 93, 486
Larwood, J. 1998, MNRAS, 299, L32
Lense, J., & Thirring, H. 1918, Physikalische Zeitschrift 19, p. 156-163

Massi, M., Ribó, M, Paredes, J. M., et al. 2004, A&A, 414, L1

Massi, M., Ribó, M., Paredes, J. M., Garrington, S. T., Peracaula, M., & Martí, J. 2005, High Energy Gamma-Ray Astronomy, 745, 311

Massi, M., & Kaufman Bernadó, M. 2009, ApJ, 702, 1179

Massi, M., & Zimmermann, L. 2010, A&A, 515, A82

Nelson, R. P., & Papaloizou, J. C. B. 2000, MNRAS, 315, 570

Ray, P. S., & Jacob M. Hartman, J. M. 2008, The Astronomer's Telegram, 1730, 1

Stella, L., & Vietri, M. 1998, ApJ, 492, L59

Taylor, A. R., Kenny, H. T., Spencer, R. E., & Tzioumis, A. 1992, ApJ, 395, 268

Taylor, A. R., Dougherty, S. M., Scott, W. K., Peracaula, M., & Paredes, J. M. 2000, proc. of *Astrophysical Phenomena Revealed by Space VLBI*, eds. H. Hirabayashi, P. G. Edwards, and D. W. Murphy, pub. ISAS, p. 223

Wilkins, D. C. 1972, Phys. Rev. D, 5, 814