Bardeen-Petterson effect as the precession mechanism for the radio galaxy 3C84 (NGC 1275)

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Abstract

NGC 1275 is a giant elliptical galaxy at the center of the Perseus cluster of galaxies. It is associated to a strong radio source (3C84) and presents X-ray emission that extends well into the intergalactic medium. The X-ray maps present multiple misaligned pairs of cavities, some of them coincident with maxima in the radio emission, which had been interpreted as bubbles inflated by a precessing radio jet. 3D hydrodynamical simulations found that bubbles can be formed only under some restricted precession conditions, and in a previous paper we proposed that the Bardeen-Peterson effect could be responsible for the torques driving this precession. In the present work we derive the radio structure expected from a jet precessing according to this process, using parsec scale radio observations as constrains and obtain the precession parameters that are compatible with both the radio image and the inflation of the X-ray bubbles. Using other properties of the radio galaxy, like bolometric luminosity, mass of the central black hole, and absorption of the radio counterjet by the accretion disk, we were able to put limits on the accretion disk parameters and on the rotation rate of the black hole.

I. Parameters of the AGN

The black hole mass was estimated by Wilman et al. (2005) as M_{BH}=3.4×10^{8}M$_\Theta$ and the bolometric luminosity by Levinson et al. (1995) as 4×10^{44} erg s^{-1}. McGregor et al. (2007) through IR observations of Fe II and molecular hydrogen found evidences of a keplerian and warped accretion disc with an inclination i=37.1°±3.4°.
Recently, Falceta-Gonçalves et al. (2010) through 3D numerical simulations were able to reproduce the X-ray maps of NGC 1275, assuming an initial rate of disk to black hole angular momentum of 1.1, an initial angle between them 120°, a precession period of 5×10^7 years and an alignment timescale of at least three times this value.
VLBI observations (Abdo et al. 2009; Nagai et al. 2010) showed that ejections of new components in the jet are still occurring at intervals of the order of decades and this allow us to consider the jet as continuous when compared with the age of the radio source. Using this observations we have also two other constrains for the jet which are that the projected angle of the jet on the plane of the sky is $\eta(t_{obs})$~170° (Asada et al. 2006) and that the angle between the jet and the line of sight, $\phi(t_{obs})$=30° – 50° (Walker, Romney & Benson 1994)

II. Accretion disc model

In this work we are considering an accretion disc with angular momentum density per unity area

$$L_d(r) = \Sigma(r)\Omega(r)r^2$$

where r is the distance to the black hole, Σ the accretion disk surface density, and Ω the Keplerian angular velocity.
We assume that the accretion disc surface density can be written as a power law (e.g Ostriker, Shu, & Adams 1992, Caproni et al. 2006, 2007):

$$\Sigma = \Sigma_0\left(\frac{r}{R_g}\right)^{-s}$$

where Σ_0 and s are constants Models show that 0<s<2. Σ_0 is an unknown constant, but its value can be estimated assuming that the radial transport is subsonic and that the disk is stable against self-gravity (Caproni et al. 2006).

In the case of NGC 1275 an expression for Σ_0 can be found using the observational constrain given by Walker et al. (2000) where using the observed absorption of the counterjet emission at low radio frequencies, they found that the emission measure of the absorbing gas at a projected distance from the core of 2.5 pc, could be represented by the law $L_{pc}n^2_eT_4^{-1.5}g_4=5.7\times10^8r_{2.5}^{-1.5}$ where L_{pc} is the projected size along the line of sight, in units of pc, n_e the electron density, in cm^{-3}, T_4 the electron temperature, in units of 10^4 K, g_4 the Gaunt factor, in units of its value at T = 10^4 K, and $r_{2.5}$ the projected distance to the core, in units of 2.5 pc. Using this constrain we were able to find an expression for Σ_0 as a function of s and a_* and has the form

$$\Sigma_0 = 7.4\times10^{-11}\left[\mu_e^4\cos^2\phi_0\frac{\dot{M}(a_*)R_g}{\alpha}\right]^{\frac{1}{5}}\left[\frac{2.5pc}{R_g}\right]^{\frac{10s+3}{10}}$$

III. Bardeen-Petterson effect

A particle moving around a Kerr black hole with mass M_{BH} will experience precession due to the Lense-Thirring effect if its orbit is non-coplanar with the equator of the black hole, defined as the plane perpendicular its angular momentum J_{BH}. The precession angular velocity Ω_{LT} is given by (e.g., Wilkins 1972):

$$\Omega_{LT}(r) = \frac{2GJ_{BH}}{c^2r^3}$$

The combined action of the Lense-Thirring effect with the inner viscosity of the disc causes the alignment of the angular momenta of the disc and the Kerr black hole; this is knows as Bardeen-Petterson effect (Bardeen & Petterson 1975) and tends to affect only the innermost parts of the disc due to the short range of the Lense-Thirring effect, while the outer parts tend to remain in its original configuration. The transition radius between these two regions is known by Bardeen-Petterson radius and its location depends of the accretion disc configuration (Bardeen & Petterson 1975; Kumar & Pringle 1985; Nelson & Papaloizou 2000, Fragile & Anninos 2005).
Considering conservation of the total angular momentum of the system formed by the accretion disk and the black hole, the torque on the black hole will be equal to the torque produced on the disk by the Bardeen-Petterson effect. We will assume that the disk is aligned with the rotation axis of the black hole up to the Bardeen-Petterson radius and maintains its original inclination farther out. Using this fact, the alignment timescale can be calculated as:

$$T_{align} = J_{BH}\left[2\pi\sin\varphi_0\int_{R_{BP}}^{R_D}L_d(r)\Omega_{LT}(r,t_0)rdr\right]^{-1}$$

where R_D is the radius of the accretion disk and R_{BP} is the Bardeen-Petterson radius defined as being

$$R_{BP} = \sqrt{\frac{\nu_2(r=R_{BP})}{\Omega_{LT}(r=R_{BP})}} = \sqrt{\frac{f(\alpha)\nu_1(r=R_{BP})}{\Omega_{LT}(r=R_{BP})}}$$

and

$$\nu_1(r) = \frac{\dot{M}}{2\pi\Sigma}\left[\frac{d\ln\Omega}{d\ln r}\right]^{-1}\left[1-\left(\frac{R_{ms}}{r}\right)^2\frac{\Omega(R_{ms})}{\Omega(r)}\right]$$

where $\nu_2(r)$ is the viscosity acting on a direction perpendicular to the disk, $\nu_1(r)$ is the azimuthal kinematic viscosity, M is the accretion rate onto the black hole and $f(\alpha)=2(1+7\alpha^2)/[\alpha^2(4+\alpha^2)]$ (Ogilvie 1999).
Finally, we will assume that the precession period is equal to the alignment timescale (T_{prec} = T_{align}), as found in analytical calculations considering steady-state configuration (Scheuer & Feiler 1996).

IV. Results

IV.I The radio image

Using the precession model of Abraham & Romero (1999) and the observational constrains, we were able to reproduce the radio image. In the figure 1 we present our model overlaid to the 0.5 – 7 keV X-ray image obtained with Chandra by Fabian et al. (2000) which is also overlaid to the 332 MHz VLA map of Pedlar et al. (1990).

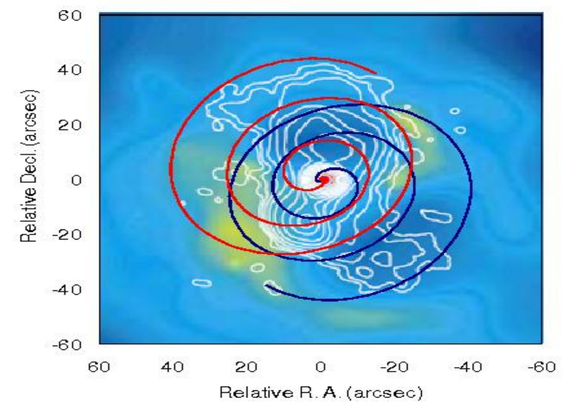

Figure 1: Precession model overlaid to the *Chandra* X-ray image and VLA 332 MHz contours (Fabian et al. 2000; Pedlar et al. 1990).

We found that the best precession parameters that fits well the jet are: ϕ_0=30, η_0=47 (measured from north to east) and v_{jet} = 100 km s^{-1}. We are also assuming that the angle $\varphi_D(t)$ follows the behavior given by the equation 19 of King et al. (2005) using $\varphi(t_0)$ = 120° and $J_D(t_0)/J_{BH}$ = 1.1.

IV.II Accretion Disk parameters

Using the equation of the alignment timescale we were able to find the alignment timescale for different values of a* and s. It is shown in figure 2. We see from the graphic that the value for the alignment timescale found by Falceta-Gonçalves et al. (2010) is only found for 0.6 <s<0.8 but we were unable to constrain the black hole spin.

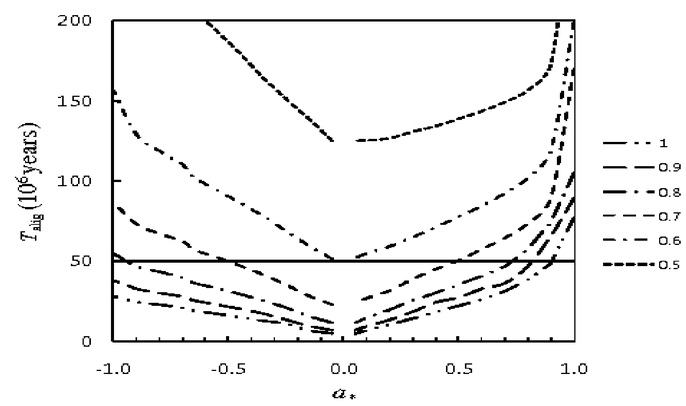

Figure 2: Alignment timescale for different values of $a*$ and s. The horizontal line represents the alignment timescale found by Falceta-Gonçalves et al. (2010).

References

Abdo, A., A., Ackermann, M., Ajello, M., Baldini, L., et al., 2009, ApJ, 699, 31
Abraham, Z., Romero, G.E., 1999, A&A, 344, 61
Asada, K, Kameno, S., Shen, Z-Q., Horiuchi, S., Gabuzda, D.C., Inoue, M., 2006, PASJ, 58, 261
Bardenn, J. M., Petterson, J. A. 1975, ApJ, 195, L65
Caproni, A., Abraham, Z., & Mosquera Cuesta, H. J. 2006, ApJ, 638, 120
Caproni, A., Abraham, Z., Livio, M., Mosquera Cuesta, H. J. 2007, MNRAS, 379, 135
Fabian, A. C., Sanders, J. S., Ettori, G. B., Taylor, G. B., Allen, S. W. et al. 2000, MNRAS, 318, L65
Falceta-Gon¸calves, D., Caproni, A., Abraham, Z., Teixeira, D.M., Gouveia Dal Pine, E. M., 2010, ApJ, 713, L74
Fragile, P. C. & Anninos, P., 2005, ApJ, 623, 347
Kumar, S., Pringle, J. E. 1985, MNRAS, 213, 435
Lense, J., Thirring, H. 1918, Phys, Z., 19, 156
Levinson, A., Laor, A., Vermeulen, R. C., 1995, ApJ, 448, 589
King, A. R., Lubow, S. H., Ogilvie, G. I., Pringle, J. E., 2005, MNRAS, 363, 49
Kumar, S., Pringle, J. E. 1985, MNRAS, 213, 435
McGregor P., Sutherland M. D. R., Beck T., Storchi-Bergmann T., 2007, Ap&SS, 311, 223
Nagai, H., Suzuki, K., Asada, K., Kino, M., Kameno, S. et al., 2010, PASJ, 62, 11
Nelson, R. P., & Papaloizou, J. C. B. 2000, MNRAS, 315, 570
Ogilvie, G. I. 1999, MNRAS, 304, 557
Ostriker, E. C., Shu, F. H., Adams, F. C. 1992, ApJ, 399, 192
Pedlar, A., Booler, R. V., Davies, R. D. 1990, MNRAS, 203, 667
Scheuer, P. A. G.; Feiler, R. 1996, MNRAS, 282, 291
Walker, R. C., Dhawan, V., Romney, J. D., Kellermann, K. I., Vermeulen, R. C. 2000, ApJ, 530, 233
Wilkins, D. C. 1972, Phys. Rev. D, 5, 814
Wilman, R. J.; Edge, A. C.; Johnstone, R. M. 2005, MNRAS 359, 755