Binary Black Holes at the Core of Galaxy Clusters

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Abstract

In this paper we push forward and exploit an analogy between the morphologies of the X-ray cavities observed in some galaxy clusters, and the optically deficient point-symmetric bubbles occurring in some planetary nebulae (PNe). Point-symmetric PNe are thought to be shaped by stellar binary interactions; namely, the presence of a companion to the PN’s progenitor star is required. We suggest that similar point-symmetric structures in the X-ray cavities of galaxy clusters might be associated with the presence of massive binary black holes. A systematic cataloguing of high-resolution images of the diffuse X-ray emission at the core of galaxy clusters might contribute to individuate massive binary black holes.

1 Introduction

In our hierarchical Universe, where small structures merge into larger ones, massive binary black holes (i.e. with $M = 10^8 - 10^9 \, M_\odot$) are believed to be fairly common. Yet, up to now there is little compelling evidence of their existence (Komossa, 2003; Merritt and Milosavljević, 2004). The strongest candidate for a massive binary black hole (MBBH) are two X-ray active AGNs at the core of the nearby ($z = 0.02$) galaxy NGC 6240 observed with Chandra (Komossa et al., 2003). These AGNs are only 1.5 arcsec apart, and this hints that the possibility for a “direct” detection of double AGNs is limited to very nearby objects. Other pieces of evidence are more indirect (Begelman et al., 1980; see also Komossa, 2003 for a recent review).

The history of a massive binary black hole may be summarised in the following steps (Begelman et al., 1980; Merritt and Milosavljević, 2004; Roos, 1988): 1) after two galaxies merge, the two massive black holes in the former galaxies’
nuclei sink into the gravitational well on account of the dynamical friction, and they eventually form a MBBH; 2) the binary orbit slowly decays, since the interactions with field stars extract energy and angular momentum from the binary system; 3) if the binary separation decreases enough, gravitational radiation takes over and the binary rapidly coalesces.

The centre of cool-core galaxy clusters is almost always occupied by a massive cD galaxy, formed by the mergers of several smaller galaxies (Dubinski, 1998). cD galaxies, therefore, seem the ideal environment to look for MBBHs.

Step 1 is quite fast, while the passage from phase 2 to phase 3 may take a very long time (Merritt and Milosavljević, 2004). Therefore, many MBBH are expected to lie in the intermediate phase 2, where their separation is still too large to allow a significant gravitational radiation emission, but where the mutual gravitational interaction is strong enough to spark interesting phenomena.

In this paper we discuss the possibility to detect MBBH at the core of galaxy clusters from a morphological analysis of their X-ray emission. Our method is based on an analogy between the morphology of the diffuse X-ray emission at the core of some galaxy clusters, and similar structures observed in the optical emission of some planetary nebulae (PNe) (Soker, 2003a,b, 2004). This similarity suggests that a common physical mechanism lies at the origin of these structures. We argue that this common mechanism is the gravitational action of a binary system.

2 Point-Symmetric Bubbles in Planetary Nebulae

Solar-sized stars loose their outer envelope during the Asymptotic Giant Branch (AGB) phase, after they quit the main sequence. The lost shell is ionised by the leftover central white dwarf, and shines as a PN. Actually, only 10% of all PNe are spherically symmetric (Soker, 1992); most of them are axisymmetric, or even completely asymmetric, with a wide spectrum of morphologies. Here we focus on bipolar PNe, which exhibit two lobes and an equatorial waist between them. A prototype of this kind of PNe is Hb 5, shown in Figure 1. Point-symmetry is another feature of this nebula. As in geometry, a structure is said to be point-symmetric if, to each substructure, a similar substructure corresponds on the opposite side with respect to the centre. In general, point symmetry does not imply neither mirror symmetry nor axial symmetry.

A pair of optically faint lobes is also apparent in this object, as well as in others PNe. The inner regions of the lobes are optically faint on account of their low density, which is about 2-3 orders of magnitude below the surroundings (Soker, 2003a,b, 2004).
The formation of bipolar PNe and point-symmetric structures can be explained by the influence of a binary companion (Soker, 2004). The AGB wind from the primary star forms an accretion disc around a secondary compact star; in turn, this accretion disc launches jets and/or collimated fast winds into the PN shell. If the jet orientation remains constant in time, the PN should possess a pure axisymmetrical structure. The bright pattern is different if the jets precess, however. During the precession motion the jets expand in a point-symmetric geometry centred on the PN core, hence inflating point-symmetric bubble pairs.

What is the cause of this precession? If the jet is fired by an accretion disc, the jet’s precession is a direct consequence of the disc’s own precession. Different mechanisms may be able to drive it.

The first one is the action of a companion star, which makes the disc precess at a rate \( \omega_{\text{prec}} \approx 0.4 \left( \frac{GM}{a^3} \right)^{1/2} \left( \frac{a_d}{a} \right)^{3/2} \frac{q}{(1+q)^{1/2}} \cos \vartheta \),

\[
\omega_{\text{prec}} \approx 0.4 \left( \frac{GM}{a^3} \right)^{1/2} \left( \frac{a_d}{a} \right)^{3/2} \frac{q}{(1+q)^{1/2}} \cos \vartheta, \tag{1}
\]

where \( q = M_2/M_1 \), \( M_1 \) is the mass of the accreting object, \( M_2 \) is the mass of the mass-loosing component, \( M = M_1 + M_2 \) is the mass of the binary system, \( a \) is the separation between the components (assuming a circular orbit), \( a_d \) is the disc’s radius, and \( \vartheta \) is the tilt angle between the disc and the orbital plane. Normalising to values typical for a stellar binary system, the precession period \( \tau_{\text{prec}} = 2\pi/\omega_{\text{prec}} \) is

\[
\tau_{\text{prec}} \approx 10^3 \text{ yr} \left( \frac{M}{2M_\odot} \right)^{1/2} \left( \frac{a}{10^{14} \text{ cm}} \right)^3 \left( \frac{a_d}{10^{13} \text{ cm}} \right)^{-3/2} \frac{(1+q)^{1/2}}{q \cos \vartheta}. \tag{2}
\]

A second possible scenario is that the PN’s progenitor is a single star. In this case, the mechanism driving the jet’s precession is a disc’s intrinsic instability, which warps the disc (Pringle, 1997) and wobbles the jet’s direction on a time scale of hundreds of years (Livio and Pringle, 1997). The two mechanisms predict similar precession time-scales, which are few times smaller than a typical PN’s age. This allows few precessions in total, enough to produce the observed point-symmetric structure.

Even if both mechanisms predict the same time-scale for precession, there is a potential important difference between the two models, which will turn out to be important when we shall extend this model to galaxy clusters. The self-induced warping instability causes the accretion disc to wobble in a stochastic
manner (Pringle, 1997; Livio and Pringle, 1997). In such a case we expect that the signature will be a point-symmetric nebula, but with no global axisymmetry. Such nebulae might have a morphology resembling that of the PN He 2-47 (see Figure 3, from Sahai, 2000), and to less extent that of the PN M1-37 (Sahai, 2000). We point out that a model based on a stellar binary system at the centre of each of these two PNe can also account for their structure. In any case, we do not expect that the self-induced warping instability will lead to a nice global axisymmetric structure — besides the point-symmetric brightness — as in the PN Hb 5 (Figure 1).

3 A Generalisation to Galaxy Clusters

In this Section we extend this physical picture to the X-ray cavities in galaxy clusters. The last generation X-ray satellites Chandra and XMM-Newton have revealed the presence of X-ray deficient bubble pairs in the diffuse medium of several cooling flow clusters of galaxies. (e.g. Hydra A: McNamara et al. (2000); Perseus: Fabian et al. (2000, 2003); A 2597: McNamara et al. (2001); A 4059: Heinz et al. (2002); RBS 797: Schindler et al. (2001); A 2052 Blanton et al. (2003)). These X-ray cavities also harbour a relevant radio emission, owing to synchrotron radiation. It is generally accepted that these cavities are associated to the activity of an AGN sitting at the cluster centre. Its outbursts may inject a sizeable amount of energy ($10^{57} - 10^{60}$ erg) into the diffuse intra-cluster medium (ICM). Magnetic fields and hot, possibly relativistic, plasma displace the dense ICM, leaving over thin and X-ray faint cavities. The absence of strong shocks at the rims of essentially all these cavities shows that the ICM displacement is quite gentle (McNamara, 2004).

In some cases the diffuse X-ray emission near these cavities exhibits a point-symmetric structure. An example is the recently observed galaxy cluster MS 0735.6+7421, whose Chandra image was first presented at the 2004 COSPAR meeting (McNamara et al., 2005, see also Figure 2). This is a faraway ($z \simeq 0.2$) cluster, thus even with Chandra its angular resolution is rather poor. To better appreciate the analogies with point-symmetric nebulae, we compare it to a low-resolution image of the point-symmetric nebula Hb 5 (Figure 1, right panel). Both structures have similar point-symmetries: as discussed above, if we suppose they are due to a precessing jet, the regular morphology hints in both cases for a binary-driven precession, rather than for a stochastic precession à la Pringle. Even in this case, the morphological criterion is the only discriminant, because the precession time scales predicted by the two models are similar:

$$\tau_{\text{prec}} \simeq 2 \times 10^7 \text{ yr } \alpha^{-1} \frac{M}{10^9 \text{ M}_\odot}, \quad (3)$$
for Pringle’s model (equation (4.11) of Pringle (1977); $\alpha$ is the celebrated Shakura and Sunyaev (1973) alpha-parameter), and

$$\tau_{\text{prec}} \approx 10^6 \text{ yr} \left( \frac{M}{10^9 M_\odot} \right)^{1/2} \left( \frac{a}{10^{19} \text{ cm}} \right)^3 \left( \frac{a_d}{10^{18} \text{ cm}} \right)^{-3/2} \left( \frac{1 + q}{q \cos \vartheta} \right)^{1/2}.$$  (4)

for the binary model. For a typical mass ratio $q = 0.1$, the precession period is $\tau_{\text{prec}} \approx 10^7$ yr, close to the value predicted by the warp-instability model. Both the estimated precession time scales are few times smaller than the estimated lifetime of the jet activity $\approx 10^8$ yr (McNamara, 2004), allowing few precession in total. We conclude this Section with a caveat. A precessing opposite-jet model may explain quite naturally a point-symmetric structure like in MS 0735.6+7421, because it can influence symmetrically both sides of the cluster’s centre. Yet, alternative explanations are by no way ruled out. High resolution X-ray imaging, stellar dynamics analysis, detailed radio observations are required to weed out the spurious candidates.

4 Summary and Conclusion

In this paper we have been guided by the occurrence of point-symmetric structures both in the X-ray deficient bubbles in some galaxy clusters and in optical deficient bubbles in bipolar planetary nebulae. We have pointed out that the ultimate origin of these symmetric structures might be binary-driven precession of the jets inflating the bubble pairs. If this hypothesis is correct, the galaxy cluster MS 0735.6+7421 should harbour a massive binary black hole at its centre.

We may look ahead beyond the special case of MS 0735.6+7421, and suggest that a systematic cataloguing of point-symmetric X-ray structures in galaxy clusters might increase the number of candidate MBBHs. For this task a high angular resolution is necessary. Chandra is suitable for that task, and in the future more candidates are to be expected in the XEUS sky.

The initial part of this research was motivated by discussions with Mordechai Rorvig. We thank Brian McNamara for useful comments. We thank Arsen Hajian, Raghvendra Sahai, and Romano Corradi for the images of the PNe. FP is supported by a Fine Fellowship at the Technion-Israel Institute of Technology. FP was supported by grant No. 2002111 from the United States-Israel Binational Foundation (BSF), Jerusalem, Israel. This research was supported by the Israel Science Foundation.
Begelman, M. C., Blandford, R. D., and Rees, M. J. (1980). Massive black hole binaries in active galactic nuclei. *Nature*, 287:307–309.

Blanton, E. L., Sarazin, C. L., and McNamara, B. R. (2003). Chandra observation of the cooling flow cluster Abell 2052. *Astrophys. J.*, 585:227–243.

Dubinski, J. (1998). The origin of the brightest cluster galaxies. *Astrophys. J.*, 502:141–149.

Fabian, A. C., Sanders, J. S., Crawford, C. S., et al. (2003). The relationship between the optical Hα filaments and the X-ray emission in the core of the Perseus cluster. *Mon. Not. R. Astron. Soc.*, 344:L48–L52.

Fabian, A. C., Sanders, J. S., Ettori, S., et al. (2000). Chandra imaging of the complex X-ray core of the Perseus cluster. *Mon. Not. R. Astron. Soc.*, 318:L65–L68.

Heinz, S., Choi, Y., Reynolds, C. S., et al. (2002). Chandra ACIS-S observations of Abell 4059: signs of dramatic interaction between a radio galaxy and a galaxy cluster. *Astrophys. J.*, 569:L79–L82.

Katz, J. I. (1997). A precessing disk in OJ 287? *Astrophys. J.*, 478:527–529.

Komossa, S. (2003). Observational evidence for supermassive black hole binaries. In *AIP Conf. Proc. 686: The Astrophysics of Gravitational Wave Sources*, pages 161–174.

Komossa, S., Burwitz, V., Hasinger, G., et al. (2003). Discovery of a binary active galactic nucleus in the ultraluminous infrared galaxy NGC 6240 using Chandra. *Astrophys. J.*, 582:L15–L19.

Livio, M. and Pringle, J. E. (1997). Wobbling accretion disks, jets, and point-symmetric nebulae. *Astrophys. J.*, 486:835–839.

McNamara, B. R. (2004). Magnetic bubbles in galaxy clusters. In *Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution.* (astro-ph/0310708).

McNamara, B. R., Nulsen, P. E. J., Wise, M. W., et al. (2005). The heating of gas in a galaxy cluster by X-ray cavities and large-scale shock fronts. *Nature*, 433:45–47.

McNamara, B. R., Wise, M., Nulsen, P. E. J., et al. (2000). Chandra X-ray observations of the Hydra A cluster: an interaction between the radio source and the X-ray-emitting gas. *Astrophys. J.*, 534:L135–L138.

McNamara, B. R., Wise, M. W., Nulsen, P. E. J., et al. (2001). Discovery of ghost cavities in the X-ray atmosphere of Abell 2597. *Astrophys. J.*, 562:L149–L152.

Merritt, D. and Milosavljević, M. (2004). Massive black holes binary evolution. (astro/ph 0410364). To appear in the *Living Reviews in Relativity*.

Pringle, J. (1997). Self-induced warping of accretion discs. Non-linear evolution and application to AGN. *Mon. Not. R. Astron. Soc.*, 292:136–147.

Roos, N. (1988). Jet precession in active galaxies. *Astrophys. J.*, 334:95–103.

Sahai, R. (2000). The starfish twins: two young planetary nebulae with extreme multipolar morphology. *Astrophys. J.*, 537:L43–L47.
Schindler, S., Castillo-Morales, A., De Filippis, E., et al. (2001). Discovery of depressions in the X-ray emission of the distant galaxy cluster RBS797 in a Chandra observation. *Astron. & Astrophys.*, 376:L27–L30.

Schwarz, H. E., Corradi, R. L. M., and Melnick, J. (1992). A catalogue of narrow band images of planetary nebulae. *Astron. & Astrophys. Suppl. Ser.*, 96:23–113.

Shakura, N. I. and Sunyaev, R. A. (1973). Black holes in binary systems. Observational appearance. *Astron. & Astrophys.*, 24:337–355.

Soker, N. (1992). Planetary nebulae. *Scientific American*, 266:78–85.

Soker, N. (2003a). The mistery companion. *Nature*, 426:236-237.

Soker, N. (2003b). Pairs of bubbles in planetary nebulae and clusters of galaxies. *Publ. Astron. Soc. Pac.*, 115:1296–1300.

Soker, N. (2004). Shaping planetary nebulae and related objects. In ASP *Conf. Ser. 313: Asymmetrical Planetary Nebulae III: Winds, Structure and the Thunderbird*. extended version on [astro-ph/0309228](http://arxiv.org/abs/astro-ph/0309228) the images of PNe and clusters of galaxies are summarized in a powerpoint file presented during the APN3 meeting (2003) available at the site: [http://www.astro.washington.edu/balick/APN/APN_talks_posters.html](http://www.astro.washington.edu/balick/APN/APN_talks_posters.html) (ppt file in the discussion of session 13).

Terzian, Y. and Hajian, A. R. (2000). Planetary nebulae with the Hubble Space Telescope. In *Astronomical Society of the Pacific Conference Series*. 7
Fig. 1. The planetary nebula Hb 5. Left panel: a HST high-resolution image (Terzian and Hajian, 2000); image by kind permission of A. R. Hajian, see http://ad.usno.navy.mil/pne/gallery.html. Right panel: a low-resolution image of the same object from the catalogue of Schwarz et al. (1992), and the original resolution was degraded by Gaussian smoothing (R. Corradi, private communication). The edge-to-edge angular distance along the major axis is 60”, corresponding to a linear scale of about 0.4 pc at the nebula’s distance.

Fig. 2. A Chandra X-ray image of the galaxy cluster MS 0735.6+7421 exhibits a point-symmetric structure. The cavities near the “arms” have a diameter of about 250 kpc (McNamara et al., 2005).
Fig. 3. The planetary nebula He 2-47 (Sahai, 2000); image by kind permission of A. R. Hajian, [http://ad.usno.navy.mil/pne/gallery.html](http://ad.usno.navy.mil/pne/gallery.html). The angular size of this PN is about 9" (Sahai, 2000).