X-ray Cavity Formation in Galaxy Clusters (Post-print)

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Abstract

A small fraction of active galactic nuclei in galaxy clusters are surrounded by giant X-ray cavities, with X-ray observations revealing that the internal energy of these cavities is 1048 ~ 1055 J. It is generally believed that the energy of these cavities originates from AGN jets. MS 0735+7421 is the X-ray cavity with the highest known internal energy, containing 1055 J. The central black hole mass is estimated from observational data to be 5 ˆ 109Md, and radio observations indicate that its current jet activity is relatively weak, with a jet activity timescale of approximately 108 a. Using the recently established stochastic accretion-jet model to investigate the formation process of the X-ray cavity in this source, it is found that jets produced by stochastic accretion can successfully explain important observational phenomena such as the total cavity energy and central black hole mass.

Full Text

Preamble

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Formation of X-ray Cavities in Galaxy Clusters

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Abstract

A small fraction of active galactic nuclei (AGN) in galaxy clusters exhibit giant X-ray cavities with internal energies of 10^{48}-10^{55} J, as revealed by X-ray observations. These cavities are generally believed to be powered by AGN jets. MS 0735+7421 hosts the most energetic X-ray cavity known, containing approximately 10^{55} J of energy. Observational data estimate its central black hole mass at 5×10^9 M , while radio observations indicate relatively weak current jet activity with an active duration of about 10^8 yr. Using a recently developed stochastic accretion-jet model, we investigate the formation process of the X-ray cavity in this source and find that jets produced by stochastic accretion can well explain important observational features such as the total cavity energy and central black hole mass.

Keywords: active galactic nuclei; X-ray cavity; jet; accretion

1 Introduction

Nearly every galaxy in the universe harbors a supermassive black hole with mass ranging from millions to billions of solar masses in its central region. Numerous observed phenomena are associated with these central supermassive black holes, with active galactic nuclei (AGN) being a prime example. AGN are characterized by an extremely compact and luminous nucleus with strong non-thermal continuum emission. While AGN are classified into various types based on different observational characteristics, they are observationally divided into four main categories: radio galaxies, Seyfert galaxies, quasars, and BL Lac objects. Galaxies with radio luminosities exceeding approximately 10^{34} J s^{-1} are defined as radio galaxies.

The cooling time of gas in galaxy clusters is less than 10^9 yr. In the absence of heating, Fabian [?] proposed a cooling flow model in 1994, suggesting that gas would cool below temperatures corresponding to X-ray radiation, be accreted toward the cluster center to form molecular clouds, and subsequently produce stars. The primary features of cooling flows are inwardly decreasing temperature gradients and short central cooling times. However, observations from Chandra, ASCA, and high-resolution XMM-Newton telescopes have revealed that in some sources, the gas temperature does not drop below 2 keV as predicted [?], implying the existence of some heating mechanism within galaxy clusters. Observations with XMM-Newton and Chandra [?, ?, ?] have discovered giant X-ray cavities with energies of approximately 10^{48}-10^{55} J in central cluster galaxies, providing direct observational evidence that ICM cooling is effectively suppressed and that AGN feedback plays a crucial role in galaxy formation and evolution [?, ?, ?, ?]. Jets from the accretion disk around the central black hole are considered the cause of these X-ray cavities. Consequently, the interaction between these cavities and the surrounding hot gas offers an effective method for measuring the energy injected by jets. Observationally, the average jet power can be estimated by measuring the cavity volume and the buoyancy rise timescale [?, ?, ?]. The radiative cooling timescale of gas in galaxy clusters is typically much shorter than the Hubble time, which would theoretically lead to the inevitable formation of large amounts of inflowing cold gas, contradicting high-resolution X-ray observations. Observations indicate that some unknown heating source must balance the radiative cooling in this interstellar medium. These X-ray cavities heat the surrounding interstellar medium during their expansion and buoyant rise. Some studies have shown that this heating process is sufficient to effectively suppress catastrophic cooling of the interstellar medium. Similar to paired radio lobes, X-ray cavities often appear in pairs with diameters ranging from several kpc to hundreds of kpc. Some observations demonstrate excellent spatial correspondence between X-ray cavities and AGN radio lobes, indirectly proving that feedback from AGN is an important energy source in the heating of interstellar medium. For details, see Fabian’ s review and references therein [?].

Relativistic jet formation requires two conditions: (1) a rapidly rotating black hole or accretion disk, and (2) large-scale magnetic fields. Over the past few decades, numerous studies have investigated jet formation mechanisms in AGN and proposed many theoretical models, which can be basically divided into two categories: the Blandford-Znajek (BZ) mechanism [?] and the Blandford-Payne (BP) mechanism [?]. Both models require the presence of large-scale, ordered magnetic fields, but differ in that the former extracts the black hole’ s rotational energy and is dominated by Poynting flux with almost no matter content, while the latter is matter-dominated and extracts the accretion disk’ s rotational kinetic energy.

MS 0735+7421 contains a giant X-ray cavity storing approximately 10^{55} J of energy and persisting for about 10^8 yr, representing one of the most energetic AGN outburst events known. If MS 0735+7421 harbors a 5×10^9 M black hole, its jet’ s average power is approximately 10^{39} J s^{-1}, about 2% of its Eddington luminosity L__{Edd}. However, observations indicate that this AGN has very low optical (I-band) radiation, L_I 2.5×10^{35} J s^{-1}, meaning its current accretion rate is too low to produce jets with power on the order of 10^{39} J s^{-1} [?]. It is well known that black hole jet energy is related to the accretion rate of the black hole accretion disk, and black hole mass growth is also related to its accretion rate. The central black hole mass in MS 0735+7421 is 5×10^9 M . If the black hole experienced a period of relatively high accretion rate during its mass growth, then its accretion rate might have been sufficient to produce jets of about 10^{39} J s^{-1}. In this paper, we use a recently proposed stochastic accretion-jet model to simulate the energy provided by jets to the X-ray cavity during the black hole mass growth process, aiming to reproduce the currently observed internal energy of the cavity (10^{55} J) and to explore the jet formation mechanism of the AGN in MS 0735+7421.

2.1 Evolution of Black Hole Mass and Angular Momentum

Typically, a black hole has two intrinsic properties: mass M and angular momentum J (ignoring charge). The spacetime properties around a black hole can be described by the Kerr metric using these two fundamental parameters. A black hole’ s deep gravitational potential well captures surrounding gas, causing it to fall toward the black hole. Due to the gas’ s angular momentum relative to the black hole, it does not fall directly into the black hole like a free-falling body. Instead, angular momentum conservation causes the gas to form an accretion disk around the black hole. The mass growth and spin evolution of a black hole through continuous accretion from the disk can be described by the following equations:

$$c^2 dM = E_{ms} dM, \quad dJ = J_{ms} dM,$$

where E_{ms} and J_{ms} are the energy and angular momentum per unit mass carried by matter at the innermost stable circular orbit (ISCO), and M is the rest mass of matter accreted by the black hole. Inside the ISCO, matter will carry this energy and angular momentum into the black hole; here we do not consider in detail the complex physical processes in the plunging region. The characteristic energy and angular momentum at the ISCO can be expressed as [**?**]:

$$E_{ms} = \frac{1 - 2M/r_{ms} + a/(Mr_{ms})^{1/2}}{\sqrt{1 - 3M/r_{ms} + 2a/(Mr_{ms})^{1/2}}}$$

$$J_{ms} = \frac{(Mr_{ms})^{1/2}(1 - 2a/(Mr_{ms})^{1/2} + a^2/(Mr_{ms}))}{\sqrt{1 - 3M/r_{ms} + 2a/(Mr_{ms})^{1/2}}}$$

where $a = J/(Mc)$ is the specific angular momentum of the black hole, and r_{ms} is the radius of the ISCO, which can be expressed as:

$$r_{ms} = \frac{GM}{c^2}\left[3 + Z_2 \mp \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}\right],$$

with

$$Z_1 = 1 + (1 - a_*^2)^{1/3}\left[(1 + a_*)^{1/3} + (1 - a_*)^{1/3}\right],$$

$$Z_2 = \sqrt{3a_*^2 + Z_1^2},$$

where $a_* = cJ/(GM^2)$ is the dimensionless spin parameter.

When large-scale magnetic fields exist around a black hole, the large-scale magnetic field entering the black hole’ s ergosphere can extract the black hole’ s rotational energy. In this case, we must consider the loss of black hole energy and angular momentum caused by the magnetic field in the evolution of black hole mass and spin. Therefore, the following correction terms need to be added to the above equations:

$$c^2\dot{M} = E_{ms}\dot{M} - P, \quad \dot{J} = J_{ms}\dot{M} - \frac{P}{\Omega_h},$$

where $\dot{M} = dM/dt$, Ω_h is the angular velocity of the black hole, and P is the power of the BZ jet [?].

By selecting appropriate dimensionless parameters, the equation can be rewritten as:

$$\frac{da_*}{dt} = \frac{\dot{M}}{M}(\tilde{J}_{ms} - 2a_*\tilde{E}_{ms}) - \frac{P}{Mc^2\Omega_h},$$

where the dimensionless parameters are defined as follows:

$$\tilde{E}_{ms} = \frac{E_{ms}}{c^2}, \quad \tilde{J}_{ms} = \frac{cJ_{ms}}{GM^2}, \quad \Omega_h = \frac{c^3}{GM}\Omega_h, \quad a_* = \frac{cJ}{GM^2}.$$

2.2 Stochastic Accretion-Jet Model

If the black hole spin direction aligns with the accretion disk rotation direction, this accretion process is called prograde accretion; conversely, if the black hole spin direction is opposite to the accretion disk rotation direction, it is called retrograde accretion. A stochastic accretion process, as the name suggests, means that black hole accretion may be prograde during some time period, and after evolution may become retrograde or continue to be prograde; conversely, if the black hole is in a retrograde accretion phase during some period, it may continue to be retrograde or may switch to prograde after evolution. Many previous scholars have assumed that the magnetic field strength is of the same order of magnitude as the gas pressure or radiation pressure in the accretion disk [?, ?, ?, ?, ?, ?, ?, ?]. Livio et al. [?] pointed out in 1999 that Ghosh and Abramowicz overestimated the jet energy from the BZ mechanism; they overestimated the magnetic field strength in the inner region of the accretion disk, resulting in excessive jet energy produced by the BZ mechanism. The strength of large-scale magnetic fields is related to the thickness of the accretion disk, and the magnetic field strength formed by the thin disk dynamo mechanism is relatively low [?]. Assuming that the toroidal component of the magnetic field on the accretion disk surface is of the same order of magnitude as the poloidal component, we can estimate the maximum jet energy extracted from the accretion disk [?, ?]. McNamara et al. [?] argued that the BP mechanism cannot produce the jet energy observed in the target source. Therefore, in this paper, we select the BZ mechanism as the primary process for jet formation in the accretion disk. Since the maximum magnetic pressure is limited by the black hole accretion disk, when the magnetic field parameter $k = 1/2$ [**?**], the jet power from the BZ model reaches its maximum, and we can obtain the maximum jet power [**?**, **?**] as:

$$P_{\max} = 1.3 \times 10^{31} a_*^2 \dot{M}^2 \frac{P_{d;\max}}{\tilde{r}_h^2},$$

where $\tilde{r}_h = c^2 r_h/(GM) = 1 + \sqrt{1 - a_*^2}$ is the dimensionless black hole radius, $M_9 = M/(10^9 M_\odot)$, and $P_{d;\max}$ is the maximum pressure of the accretion disk. According to standard disk theory, when the black hole accretion rate is higher than the critical accretion rate $\dot{m}_c$, the maximum pressure of the accretion disk can be approximated as:

$$P_{d;\max} = 2 \times 10^7 (\alpha M_9)^{-1} R_1,$$

where $\dot{m} = \dot{M}/\dot{M}_{\mathrm{Edd}}$, $\dot{M}_{\mathrm{Edd}} c^2 = 1.3 \times 10^{40} M_9$ J s^{-1}, $\eta = 1 - \tilde{E}_{ms}$, and α is the viscosity parameter. The critical accretion rate $\dot{m}_c$ is defined as:

$$\dot{m}_c = 2.4 \times 10^{-4} (\alpha M_9)^{-1/8} \dot{m}^{-1/2},$$

where $R_1 \approx \tilde{r}^{-3/2}$ and $R_2 \approx \tilde{r}^{-5/2}$. Substituting the expression for $P_{d;\max}$ into the equation for $P_{\max}$ yields the maximum jet power:

$$P = 2.6 \times 10^{38} M_9 a_*^2 \frac{R_1}{\tilde{r}_h^2}.$$

Substituting this into the black hole evolution equation, we obtain the black hole mass and spin evolution equations with jet corrections (time in units of years):

$$\frac{da_*}{dt} = 2.29 \times 10^{-9} \dot{m} \left(\tilde{J}_{ms} - 2 a_* \tilde{E}_{ms} \right) - \frac{P}{Mc^2 \Omega_h}.$$

3 Results and Discussion

Section 2 introduced the main model. By solving the evolution equations, we can obtain the evolution of black hole mass and spin over time considering jet effects. The specific value of the viscosity coefficient α remains uncertain, with magnetohydrodynamic numerical simulations giving a wide range such as $\alpha = 0.01 - 1$ [**?**]. In all calculations, we adopt a viscosity coefficient $\alpha = 0.01$, ignore other possible torque effects at the inner edge of the accretion disk (i.e., the angular momentum carried by matter falling into the black hole equals that at the ISCO), and set the timescale of black hole jet activity to 10^8 yr. We calculate the total energy contributed by jets during continuous accretion. For the stochastic accretion process, we consider three different single accretion episode durations: $\tau = 10^7$ yr, $\tau = 5 \times 10^6$ yr, and $\tau = 10^6$ yr. The total accretion timescale in the calculations is 10^8 yr, composed of multiple accretion episodes of duration τ, with continuous transitions between episodes but random accretion disk angular momentum directions in different episodes.

[Figure 1: see original paper] shows the evolution of black hole mass under stochastic accretion. We select different initial black hole masses such that the final mass reaches $5 \times 10^9 M_\odot$ after 10^8 yr of accretion activity. The figure demonstrates that shorter single accretion episodes τ lead to faster black hole mass growth and thus require lower initial masses; conversely, larger initial masses are needed when τ is longer to reach $5 \times 10^9 M_\odot$ within 0.1 Gyr. For the same τ, larger Eddington ratios $\dot{m}$ result in faster black hole mass growth and thus smaller initial masses.

Figure 2a [Figure 2: see original paper] illustrates the evolution of black hole spin during stochastic accretion. For the same accretion episode τ, larger Eddington ratios $\dot{m}$ produce greater black hole spin energy because more matter is accreted within the same time, resulting in more total angular momentum entering the black hole and rapid spin increase. For different accretion episodes τ, since the angular momentum per unit mass carried by matter in prograde orbits at the ISCO is significantly smaller than that in retrograde orbits, the stochastic accretion process has the effect of reducing black hole spin—i.e., shorter τ yields average spin values closer to 0. Figure 2b shows the evolution of maximum jet power over time. For accretion episodes $\tau = 10^7$ yr and $\tau = 5 \times 10^6$ yr, the maximum jet power can exceed 10^{39} J s^{-1} for extended periods. When $\tau = 10^6$ yr, the maximum power is always less than 3×10^{39} J s^{-1}, primarily because the spin-down effect of stochastic accretion is stronger for smaller τ, keeping the overall black hole spin low, while total jet power depends strongly on black hole spin, resulting in lower maximum jet power.

[Figure 3: see original paper] presents the evolution of total jet energy over time. For accretion episodes $\tau = 10^7$ yr and $\tau = 5 \times 10^6$ yr, the final total jet energy can exceed 10^{55} J, which is roughly comparable to the energy stored in the X-ray cavity of MS 0735+7421 and can well explain the observational results. For $\tau = 10^6$ yr, the final achievable total energy is less than 10^{55} J. Therefore, if the central black hole in this source experienced multiple stochastic accretion episodes, the episodes cannot be too short, as excessively short episodes would produce insufficient total jet energy to explain current observations. We also calculated the evolution of relevant black hole parameters for continuous accretion, shown in [Figure 4: see original paper] and [Figure 5: see original paper]. Compared with stochastic accretion, continuous accretion requires an initial black hole mass exceeding $10^9 M_\odot$, results in faster final black hole spin, and can produce total jet energy exceeding 10^{55} J. However, the formation process of black holes as massive as $10^9 M_\odot$ remains unclear. Moreover, X-ray cavities formed through continuous accretion would have central black holes with spin $a_* \approx 1$, which would be expected to produce strong jets—seemingly inconsistent with observations. We propose that the X-ray cavity in MS 0735+7421 was likely powered by jets from stochastic accretion onto the central supermassive black hole.

In our model calculations, we assume the central galaxy remains continuously active. In reality, galaxies should only be active during partial time periods (e.g., Figure 14 in reference [12] [Figure 14: see original paper]), but for MS 0735+7421, a system with extremely energetic X-ray cavities, the central galaxy may be special and perhaps remains continuously active, i.e., with a duty cycle approximately equal to 1. Therefore, our calculation results may represent an upper limit to the actual situation, which warrants further investigation. Additionally, our model only considers contributions from the BZ process, as under most circumstances the BZ process energy is much higher than the BP process [**?**]. However, for cases where $a_* \approx 0$, the BP process becomes more important. If we include energy produced by the BP process, the total energy would be larger than current calculations, potentially allowing us to explain the observed X-ray cavity energy even with a smaller duty cycle. In future work, we will discuss the role of outflows formed through the BP mechanism in X-ray cavity formation.

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