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Stellar-mass black hole spinning and its relation to transient jets

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Abstract. Despite the vast research on spinning black holes and jets, little is known about details of jet formation. This paper is aimed to study whether Penrose's prediction that black hole spin power jets can be verified. Once proved, a deeper understanding of energy/momentum transfer near event horizon is to be achieved. This paper compares two dominant spin measuring methods. Thermal continuum fitting method makes use of thermal emission to measure the spin, where a theoretical flux profile is created by inputting parameters (inclination of X-ray binaries, distance of X-ray binaries from the earth, mass of black hole, etc). X-ray reflection method uses broadened Fe-line to measure the spin, and that corona geometry is often required. This paper also compares various definitions of jet power and spin-jets relation. In conclusion, transient jets are highly possible to be powered by black hole spin, but more evidence is required to confirm this. Steady jets remain in a vague relation with spin. It has also been found that different measuring methods of both spin and jets can affect the spin-jets relation.

Keywords: transient jet, black hole spin, x-ray binaries, jet power

1. Introduction

Black holes are remarkably simplest objects in our universe. In the study of spinning black holes, scientists usually take mass (M) and spin (a_*)[1] as two of the most defining parameters [1]. For a reason that only these two properties can influence on the structure of space time around a spinning black hole, according to Kerr solution [2]. In convention, black holes are classified based on their mass, ranging from stellar-mass black holes (BHs) in X-ray binaries to supermassive BHs in active galactic nuclei.

During the outbursts of stellar-mass BHs, beams of ionized particles are witnessed to be ejected from poles, including steady (compact) jets and relativistic (transient) jets. These jets carry matter, energy and momentum to the vicinity. Steady jets contain charges that are non-relativistic and normally exist on the scale of a few astronomical units. In contrast, transient jets generally take on a larger scale up to a few parsecs, and travel much faster (close to the speed of light). Scientists hypothesized that BHs spin may contribute to jets formation. In fact, Penrose has brought forward the exact idea that spinning black

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[1] Spin parameter (a_*) is defined as Jc/GM^2, where J is angular momentum of the spinning black holes, c is the speed of electromagnetic waves in vacuum, G is the gravitational constant, M is the mass of black holes

hole has free energy to spare in 1969 [3]. Later in 1977, Roger Blandford and Roman Znajek proposed the Blandford-Znajek (BZ) process, stating that transient jets can be powered by twisted magnetic field lines threading through spinning black holes [4~6]. While in 1982, Blandford and Payne proposed another Blandford-Payne (BP) process, suggesting that matter can be centrifugally removed from the surface of accretion disk by magnetic field lines leaving from the disk to create jets [7].

This paper will focus on BZ process and study whether we can verify spinning as the energy source of transient jets. Once proved, many breakthroughs are to be expected afterwards. Firstly, it will bring a better understanding in terms of how energy flow and transfer near event horizon, as well as the role played by the spiraling magnetic fields. This is going to take us a step further towards the secrets of black hole's inner structure. Secondly, it will become possible to measure spinning by investigating its transient jets only. This new method may make up for some drawbacks from existing measuring methods. Thirdly, it will also give us some insights on the future of spinning BHs as the last energy source in the universe.

In section 2, we will discuss measuring methods of BHs spin and definitions of transient jet power respectively. In section 3, we will be comparing different theories and their findings. In section 4, we will be drawing a conclusion of this paper and discuss any future implications.

2. Black hole spin and jets

2.1. Measuring black hole spin

As one of the two basic parameters to describe a BH, the measurements of spin are of great interest to current study. Besides, it is also vital to understand the astrophysical phenomena related to spin, such as whether the transient jets can be driven by spin. It has been proved that innermost stable circular orbit (ISCO) varies monotonically with spinning. It falls from $6\mathrm{GMc}^{-2}$ to GMc^{-2} as spinning parameter increases from 0 to 1. Based on this fact, scientists have been used ISCO radius to determine Black holes' spinning for decades. Two of the most dominant methods are X-ray reflection and thermal continuum fitting (CF) methods.

X-ray reflection method uses the broadened Fe-line profile to locate ISCO. Photons emitted from inner accretion disk get Inverse Compton scattered by hot electrons from the corona, causing a so-called reflection spectrum. For spinning black holes, Fe-line is broadened extensively due to Doppler boosting and gravitational red shifting, producing a "red wing" extended down to a few keV. This signature allows scientists use the extent of reddening to measure black hole spin [2].

Continuum fitting method uses broadband thermal emission of accretion disk to locate ISCO, on basis of Stephan-Boltzmann law. It starts by measuring temperature and flux, which can be done from a single X-ray observation. Then the calculated inclination (i) and distance (D) are used to obtain ISCO radius. Once ISCO radius and mass (M) are both known, spin parameter becomes fully determined. To achieve this, scientists fit X-ray spectrum into the Novikov-Throne (N-T) model, a theoretical flux profile representing thermal emission from accretion disk as a function of radius and spin. During this simulation, one needs to input exact values of parameters (i, D, M, etc), which can be difficult to obtain in the case of cold super massive black holes. Therefore, CF method is mostly used in stellar-mass black holes in X-ray binaries. On the opposite, X-ray reflection method is independent on mass, making it suitable for all kinds of BHs. But it faces a challenge of simulating the complicated coronal geometry and disk ionization process.

2.2. Measuring jets

BH X-ray binaries spend most of their lives in faint quiescence state before going through a bright outburst close to Eddington limit. Apart from an increasing amount of electromagnetic waves, black holes also eject fast-moving charges from poles, known as radio jets. Steady radio jets, which are non-relativistic and short-ranged, appear in rising and quenching state with a shape of a cone. Transient radio jets, which are more relativistic and long-ranged, occur during hard to soft transition, looking like a pair of blobs [8-9]. Once ejected form BHs, those jets go through synchrotron events in magnetic field and emit large amount of radio waves, near infrared and light [10]. For decades, the extra electromagnetic emissions have been regarded as a perfect indicator of jet power.

In 2012, Narayan and McClintock chose maximum radio luminosity at 5GHz as a measure of jet power. They defined jet power as:

$$P_{jet} = (vS_v)_{5GHz} D^2/M \tag{1}$$

where v is the frequency picked at 5GHz, Sv is the peak flux density at 5GHz, D is the distance of the BH X-ray binaries from the earth, and M is the black holes mass [11]. This definition of jet power is kept for use in later research by Steiner in 2013 and Chen in 2016 [12-13].

In 2013, Russel, Gallo and Fender chose total energy of a synchrotron flare as a representation of jet power. They suggested peak radio luminosity may not capture the whole picture of the jet energizing process since each flair has different temporal profiles [14]. They defined jet power as:

$$P_{jet,min} = (c\Delta t)^{9/7} L^{4/7} \tag{2}$$

where L is the peak radio luminosity and that Δt is the time over which a flair is radiated [14].

3. Results and discussion

Over more than half a century, scientists have measured several stellar-mass black holes in X-ray binaries to study the spin-jets relation. As stated in section 2.2, various definitions of jet power have been proposed so far. The results are presented below.

In 2012, Narayan and McClintock (NM 2012) focused on transient jets from 4 BH X-ray binaries (A 0620-00, XTE J1550-564, GRO J1655-40, GRS 1915+105) [11]. Based on the spin results via CF method, jet power is found to be proportional to the square of both spin parameter and angular frequency, i.e., $P_{jet} \propto a^2$, as shown in Fig 2 in NM 2012. It was also exciting that the results agree well with BZ model proposed in 1977 [4,11]. In 2013, Steiner, McClintock and Narayan (SMN 2013) successfully fit another source (H 1743-322) into the expected best-fit curve [12]. According to Fig.1 from SMN 2013, as spin parameter (a*) varies from 0 to ± 1, jet power increases monotonically up to 30 and performs a concave curve, based on a Lorentz factor of 2. As Lorentz factor reaches 5, this jet power becomes stronger up to 1000 [12]. In 2016, Chen et.al imported another source of X-ray binaries (Nova Muscae 1991) on top of Steiner's data, however, data point of Nova Muscae appears to be a bit lower than the best-fit curve (less correlated) by one order of magnitude [13].

In 2013, Russel, Gallo and Fender (RGF 2013) focused on transient jets as well and added seven additional BHs on top of Steiner's data (GRS 1124-68, 4U 1543-47, XTE J1652-453, GX 339-4, XTE J1752-223, Cygnus X-1, GS 2000+25) [14]. They used Bayesian linear regression analysis with inclination angle and Lorentz factor as free parameters, as opposed to Steiner's method where Lorentz factor is set at 2 and 5. To study spin-jets relation, they compared two spin measuring methods as well as two jet power definitions mentioned in section 2, which add up to four combinations in total. According to Fig.1 from RGF 2013, the most positive spin-jets relation exists in the one taking radio flare peak luminosity as jet power and CF method as spin measuring method, while other three combinations hardly perform any spin-jet relations. However, further linear regression analysis verifies only 60% of gradients are positive even in this most-related case. Therefore, they concluded that it is still too early to confirm this a positive spin-jets correlation based on current data [14]. In their early paper, they also studied steady jet power, and found steady jets are even less positively correlated to spin than transient jets [10].

4. Conclusion

This paper focused on stellar-mass black holes in X-ray binaries and intended to study the source of jet formation from the perspective of BH spinning. This paper compared two current measuring methods of black hole spin. Reflection methods uses broadened Fe-line to measure BH spin. It suits all types of BHs, but complex simulations of corona geometry and disk ionization are required. CF method creates a thermal flux profile based on parameters such as i, M, D and is widely used among stellar-mass BHs.

This paper then compared two definitions of transient jet power. Narayan, McClintock and Steiner preferred peak radio luminosity as jet power. They discovered transient jet power is proportional to the square of spin parameter i.e., $P_{jet} \propto a^2$ via CF method, which agreed well with BZ prediction [11]. Russel, Gallo and Fender insisted total flare energy as jet power and added seven more BHs to the study. They also compared two definitions of jet power and two spin measuring methods. With the help of Bayesian linear regression analysis, they concluded that the positive spin-jets relation is still yet to be confirmed based on current data [14].

In summary, transient jets are very likely to relate to black hole spin in a positive way, but more evidence is required to verify that BH spin powers jets [10-14]. Secondly, different selection of data, measuring methods of spin and definitions of jet power are all proved to affect the correlation between transient jets and spin [10,14]. Thirdly, steady jets are less possible to energize from black hole spin compared to transient jets. Finally, uncertainties from spin and jet measurements as well as lack of parameters have a certain impact on the results [10,14].

For now, we are facing tricky challenges such as lacking data and uncertainties from measurements. With less than 70 BH X-ray binaries discovered so far, few of them were fully measured. Besides, black holes spent most of their lifetime in faint quiescence state, making it rather difficult for us to capture sufficient data of outburst. In future, we could work on the resolutions of telescopes and try optimizing current models. Meanwhile, we could also measure existing BHs by various methods and compare them in detail.

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