Measurement method of black hole spin and its application in jet

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Abstract. Spin is an important property of black holes. The formation of jet and black hole is related to spin. At present, there are two commonly used spin measurement methods, the X-ray reflection method, and the continuum-fitting method. By analyzing the distribution of black hole spin in black hole binary system measured by these two methods, we find that in high-mass X-ray binaries, black holes have high spin, this is because the companion stars have a large mass and short lifetime, the black holes don’t have enough time to accelerate the spin by accretion so must be bored with high spin. However, in low-mass X-ray binaries, the spin will be widely distributed because they have enough time to increase spin by accreting gas. And according to the existing data, we can also get the relationship between spin and jet. However, both methods are affected by the complex physics of the accretion disk, in the future, gravitational waves will become another effective tool to measure the spin of black holes.

1. Introduction

When a massive star steps into the end, its energy produced by fusion can’t compete with gravity, so the star will collapse, cause a supernova explosion, then the star becomes a black hole.

According to the no-hair theory, a black hole can be specified completely by three parameters, spin (a*), mass (M), and charged quality. In celestial mechanics, we usually think that the charge of a black hole is zero (even if a black is charged, it is neutralized by the charge in the surrounding environment) [1], so spin is the focus of our discussion.

The spin is usually defined as a nondimensional parameter \( a* = \frac{cJ}{GM^2} \), \( c \) is the speed of light, \( J \) is angular momentum, and \( G \) is Newton’s constant of Gravitation [2,3]. The spin is a very important parameter, spin can be a potent energy source for powering relativistic jet and energetic particle acceleration, the jet will be ejected into the host galaxies, influence the galaxy's form and evolution. Also, spin can test the prediction of general relativity [2], and to explore how massive black holes are formed, the black hole is rapidly spin or not can show the black hole is formed by the merger of small black holes or coherent disk-accretion [3].

In section 2 of this paper, we will first introduce two methods to measure the spin of black holes, then analyze the known spin results in section 3, and then introduce the jet and its relationship with the spin in section 4, and finally give a conclusion.

2. Two methods of measuring black hole spin

Either method is based on the fact that at a moderate accretion rate, the accretion disk is geometrically-thin and optically-thick, we can regard the radius of innermost stable circular orbit (ISCO) and inner radius as equal [1,2,3]. This relationship has been proved both in observation and
theory [4]. In short, inside ISCO, the gas will fall into the black hole dynamically because of no stable orbit, so we think that ISCO is the inner edge of an accretion disk [1]. And if we get the value of $R_{ISCO}$, we can use the following equations (1) - (4) [3] to get the spin value of the black hole.

In equation (1), $\mp$ is for gas in prograde/retrograde orbits, prograde means the disk rotating in the same direction as the black hole, and retrograde means rotating in the opposite direction [3].

$$ R_{ISCO} = (3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)])^{1/2} R_g $$

(1)

$$ R_g = GM / c^2 $$

(2)

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

(3)

$$ Z_2 = (3a_*^2 + Z_1^2)^{1/2} $$

(4)

Figure 1. This figure shows the linear relationship between ISCO and $a_*$ from equation (1). Negative values of $a_*$ correspond to retrograde orbits. Note that when the accretion disk at a retrograde orbit around a maximally spinning black hole, $R_{ISCO}$ is $9R_g$. $R_{ISCO}$ is $6R_g$ for a non-spinning black hole, and for a prograde orbit around a maximally spinning black hole, $R_{ISCO}$ is $R_g$.

From figure 1, we can see that $R_{ISCO}$ is different for different spin values, which provides us with an opportunity to obtain $R_{ISCO}$ values. For example, the emission line created from the inside of the accretion disk which is closer to the black hole, more redshift will occur under gravity, so we can get the value of $R_{ISCO}$ by analyzing the broadening and degree of distortion of the emission line (X-ray reflection method). And since the inner edge is the hottest part of the disk, the high-temperature cut-off
point of the spectrum will vary with R_{ISCO}, so we can also get the R_{ISCO} by analyzing the thermal spectrum of the accretion disk (continuum-fitting method) [1].

2.1 X-ray reflection method (RE)

So far, one of the most widely used techniques for measuring spin is the X-ray reflection method, it based on the gravitational redshift of atomic features in the X-ray spectrum [2].

The black hole corona is located above the accretion disk which has lots of high-temperature (10^9K) plasma, the thermal X-ray spectrum produced by the accretion disk interact with the high-temperature plasma, causes Inverse Compton Scattering, and produces hard X-ray emission. The chemical elements on the surface of the accretion disk are strongly radiated by these hard X-rays and cause the Compton effect [2]. The electrons in the inner layer of the element are excited by photons, leave the atoms and cause the inner cavity. The electrons in the outer layer fill the cavity by releasing energy, and the released energy is emitted in the form of light(X-ray), this process is called X-ray reflection [1,2,3,4]. The most obvious emission line is the K-shell emission line of iron at 6.4keV (6.4keV-6.97keV according to the ionization state).

However, there is always a shift between the observed emission lines and the theoretical values, because the emission line is broadened and skewed by the relativistic Doppler effect, beaming effect and gravitation redshift [1,2,3].

Due to the influence of the relativistic Doppler effect, the two peaks of the double-peak emission rise, and then under the action of the beaming effect, the peak on the right increases again, while the peak on the left drops, plus the effect of gravitational redshift, the emission line profile whole is shifted to the left [1,2,3].

And a black hole with a larger spin value is more violently affected by gravitational redshift (the emission line has a lower frequency and extends to lower energies longer). This is due to a black hole with a faster spin ISCO is closer to the black hole, resulting in stronger gravitational influence [1].

There are also other interference factors, such as the X-ray reflection of the far gas, the absorption of X-ray by our galaxy and host galaxy, the accretion disk wind and so on. So we need to choose the corresponding model to deal with these [1,2].

The advantage of the X-ray reflection method is that it does not need to know the mass of the black hole, its distance from us and the inclination of the accretion disk, so it is suitable for both AGN and X-ray binary systems [2].

2.2 continuum-fitting method (CF)

Spin will affect the temperature of the accretion disk, and the closer to the black hole, the faster the gas moves, the more intense the friction between the gases, and the higher the temperature. Therefore, the temperature change of the accretion disk is similar to that of a concentric circle [1]. However, inside the ISCO, there's not enough material to interact to provide heat, the rise of temperature is terminated [5], so we can obtain ISCO by analyzing the thermal spectrum of the accretion disk, and further obtain the spin value.

This method is different from the X-ray reflection method. To build the thermal spectrum model, we must also understand the mass of the black hole, the inclination of the accretion disk, and the distance from the earth [1,2,3].

According to the formula \( a_\star = cJ/G*\pi m^2 \) [2,3], to obtain the spin value, mass is indispensable, and according to \( L = 4\pi r^2 F \) [1], the thermal spectrum we receive on earth is affected by the distance between the target black hole and the earth. Besides, we need to know the inclination to analyze the Doppler effect produced by the motion of gas at different speeds on the accretion disk [1].

This "thermal continuum fitting" technique is particularly effective for stellar-mass black holes in X-ray binary systems. In these systems, the temperature of the internal accretion disks is so high that their emission lines are in the low energy X-ray part of the spectrum, which can penetrate the dust and gas of the galaxy. However, in AGN, the application of the thermal continuum fitting method is
challenging. Because the mass of black holes is usually highly uncertain, and the internal accretion disk is relatively cold (10⁵K) [2], most of the radiation produced is in the far-or-extreme ultraviolet region of the spectrum, which can be absorbed by the gas in the Galaxy [2], make us can’t get a clear radiation spectrum.

3. Analysis of spin results

Table 1. Black hole masses and spins.

| Source          | Mass*(M☉) | RE  | CF      | reference |
|-----------------|-----------|-----|---------|-----------|
| persistent      |           |     |         |           |
| LMC X-1         | 10.9±1.4  | >0.55 | 0.92±0.05 | [5]/[3]/[5] |
| M33 X-7         | 15.65±1.45 |     | 0.84±0.05 | [5]/-/[5] |
| Cyg X-1         | 21.2±2.2  | >0.9985 |         | [11]/-/[11] |
| transient       |           |     |         |           |
| LMC X-3         | 7.6±1.6   |     | 0.25±0.13 | -/[3] |
| XTE J1650-500   | ≤7.3      | 0.79±0.01 |         | [3]/- |
| A 0620-00       | 6.6±0.25  |     | 0.12±0.19 | -/[3] |
| GRS 1915+105    | 12±2      | >0.97 | >0.95   | [3]/[3] |
| GRO J1655-40    | 6.3±0.5   | >0.9 | 0.7±0.1 | [3]/[3] |
| XTE J1550-564   | 7.8-15.6  | 0.33-0.77 | 0.34±0.37 | [3]/[3] |
| GS 1354-645     | ≥7.6±0.7  | >0.98 |         | [3]/- |
| GX 339-4        | 2.3-9.5   | >0.95 |         | [3]/- |
| 4U 1543-475     | 9.4±1.0   | 0.67±0.15 | 0.8±0.1 | [3]/[3] |

*Mass of transient black holes come from the website: http://www.astro.puc.cl/BlackCAT/. Source of persistent black hole mass are mentioned in the fourth column of the table (reference). Figure 2. This figure shows the relationship between the spin value and the mass of the black hole. If the quality value is a range, we take its average as the value in the figure. And for transient black hole systems, we use the blue point, for persistent black hole systems we use the red point. In the table, the spin values obtained by the two methods are basically the same, except GRO J1655-40 [3], for this black hole, we choose 0.7±0.1 as its spin, for other black holes which have two values, we choose the value got from the continuum-fitting method.

We usually divide the black hole binary system into low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HXMBs) according to the relative mass of the companion star. Because the companion star in HXMBs has a large mass and can continuously produce stellar wind, the black hole radiation we observed is relatively stable. We call this kind of black hole “persistent”. In contrast, in LMXBs, we call this kind of black hole “transient” because the companion star cannot provide the accretion matter continuously [5,6].

In table 1 shows both “persistent” and “transient” black holes’ masses and spins, measured via X-Ray reflection and continuum-fitting method, in order to see the relationship between the data more
clearly, we make figure 2.

From figure 2, we can find that the “persistent” black hole systems have high spin, but the “transient” black hole systems’ spins range widely. We usually think that in HMXBs, because massive stars usually evolve very fast, even if the black hole accretion rate reaches the Eddington limit [1], they can't get enough spin before their companion stars die, so they must be born with high spin. Observation also proves that the “persistent” black hole is relatively young (<10^7 yr [5]). In LMXBs, black holes have enough time to accrete gas to increase spin, so their life is generally longer, and the spin velocity observed now will be widely distributed [5].

4. Application of spin in jet

Before falling into the black hole, part of the matter in the accretion disk will gain huge energy through some mechanisms, so as to escape the accretion process before entering the event horizon. These matters form jets. The movement of these jets is generally relative, and some of them are even close to the speed of light [10]. Due to the optical aberration and observation angle, the speed we observed on the earth is even faster than that of light [1,10].

We usually divided the jet into two kinds, steady jets, and ballistic jets [5]. The steady jets are observed as a continuous outflow of plasma in the hard spectral state, this jet is small-scale, being observable only out a few tens of AU. Ballistic jet usually appears near the time of outburst maximum, when the source changes from a hard state to a soft state through the “steep power-law” state [1,5]. We generally believe that there are two ways to produce jets.

4.1 Blandford—Znajek model

According to the Penrose process, we believed that it is possible to use the energy of spinning black holes [5]. So Blandford Znajek proposed a method of black hole jet generation. Due to the frame-dragging caused by the rotation of the black hole, the magnetic lines around the black hole will
also be twisted. Therefore, the original polar magnetic lines produce an axial component, which produces Poynting flux. Then negative flux enters into the ergosphere, produced positive flux which gets energy from the black hole, this energy accelerates matters and makes them leave the black hole as a jet [5,10].

4.2 Blandford—Payne model
Unlike the previous model, Blandford—Payne model extracts energy from the accretion disk.

The ratio of gas pressure to the magnetic pressure is expressed by \( \beta = nkT/(2\mu_0B^2) \) [1], we know that the magnetic field near the accretion disk is very strong, so the flow is determined by the magnetic field, and the gas is forced to move along the magnetic field lines, just like a bead on a wire [1,10].

When the angle between the magnetic line of force and the accretion disk is less than the critical value, the gas will move outward along the magnetic line of force. Here, the energy of motion essentially comes from the rotational energy of the accretion disk [10].

From the work of Ramesh Narayan, jet power can be expressed as:

\[
P_{\text{jet}} = D^2(\nu S_{\nu})_{\text{max,5GHz}} / M D
\]

where, \( D \) is the distance, \( M \) is black hole mass, and chooses the 5-GHz peak radio flux. Then plotted a figure about \( \log a^* \) and \( \log P_{\text{jet}} \), we can see from the figure that \( P_{\text{jet}} \propto a^* \), so we think that the spin of a black hole is related to the jet [8,9].

5. Conclusion
In this paper, we first discussed two methods of measuring spin. Although we have used them to measure the spin values of many black holes, both methods have their limitations.

For the X-ray reflection method, the amount of emission lines generated by the gas on the accretion disk will be affected by its physical conditions, at different positions the conditions are different, so we cannot determine the location of ISCO based on the sudden decrease in amount of emission lines. (Maybe some areas have thin chemical elements and not enough emission lines are produced, we may judge this area as ISCO) [1]

And for the continuum-fitting method, according to our previous discussion in section 2.2, we can’t use this method to get the AGN spin value, also, this method needs to get the values of the other three parameters, which will be more possible to make errors.

Now, with the development of technology, it is possible to measure the spin of a black hole by gravitational wave. When two black holes merge, a huge gravitational wave signal will be generated [1,2]. It is by analyzing these gravitational waves that we can obtain spin information. The advantage of this method is we don’t need to consider the complex physics of accretion [3].

Then in section 3, we collected black hole spin values measured in two ways, find that the “persistent” black hole systems have high spin, but the “transient” black hole systems’ spins range widely, it shows the relationship between the companion star mass and the black hole spin value, we get a result that in HMXBs, black holes must be born with high spin because they can't get enough spin by accretion before their companion stars die. However, in LMXBs, the spin can be widely distributed because they have enough time to accrete gas to increase spin.

And for jets, at present, we still can't determine the mechanism of jet formation, the composition of jets, the relationship between jets and spins, etc. The above discussion is based on the hypotheses put forward by existing data. These need more observational data to confirm.

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