Measurement of Black Hole Spin via X-ray Reflection Spectra

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Abstract. The measurement of black hole spin is of great significance. The methods of measuring the spin have been discussed for a long time. For this important astrophysical problem, the paper begins with the significance of measuring a black hole spin and focuses on the theory of measuring the spin via the X-ray reflection recognized as iron line spectrum method. The paper also discusses the popular reflection models and explains the important parameters. Besides, the other methods of spin measurement are introduced, mainly comparing them with the X-ray reflection method. Finally, the advantages and disadvantages of the X-ray reflection method are summarized.

1. Introduction
The formation of black holes has long been a topic of interest, but no matter how complex the process is (though we still have not figured it out yet), the result is as simple as most elegant physics equations. Wheeler described it as “black holes have no hair”. In astrophysics, mass M and angular momentum J completely characterize black hole. Interestingly, with the recent research of the physical quantities of black holes, the angular momentum J, also represented by spin of the black hole, which with regard to spin parameter \( a_\ast = \frac{cJ}{Gm^2} \), is showing more and more meaningful phenomena.

One is whether the black hole spin is the source of the energy carried by jets. After Penrose first proposed that spin black holes have free energy, Narayan & McClintock pointed out in 1977 [1] that as a spinning black hole is crossed by magnetic field lines which generated by an external current flowing on the equatorial disk, and after that, energy and angular momentum can be extracted from an electric potential difference generated by it. Such a mechanism could help generate electromagnetic jets, and in theory the correlation between spin and jets energy is convincing. In the experiment, Narayan & McClintock [2] presented the relationship between spin and jet energy for the first time through the method of continuous fitting in 2013. And now, with further research, the relationship between black hole spin and jet has been developing.

One is detecting the merger of two supermassive black holes in a radio galaxy, in which the black hole's spin plays an important role. In 2002 Merritt & Ekers presented [3] that they considered whether black hole mergers could alter the spin axis of large black holes and produce measurable geometric features in radio detections of merging galaxies. The basis is that even small merging black holes can have their spin axes dramatically changed, and information about black hole mergers can be determined through measuring spin.

The spin of black holes plays a major role in the study of astrophysics, and the measurement of the spin has become an important direction in the study. Now we can measure the spin mainly by means of analyzing the Fe line spectrum, continuous radiation, high frequency quasi-periodic oscillation (HFQPO) and future X-ray polarization measurements may also provide supplementary data.
independently. In addition, there has been some development in gravitational wave measurement of black hole spin and image of a supermassive black hole through the event horizon.

In this article we will give a detailed introduction to the method of X-ray reflection spectrum which occupies an important position. Section 2 will introduce forming mechanism of X-ray reflection spectrum, and Section 3 will for existing X-ray reflection spectrum measurement of spin model to do a detailed discussion. The other methods measuring the spin we will in the Section 4 do a simple introduction. In the last part of the paper, we will summarize the methods of measuring the spin of X-ray reflection spectrum.

2. X-ray Reflection Spectrum

There are two things that we need to know before we measure the spin when we consider the accretion disk of a black hole is in the standard geometrically thin, optically thick state. The first thing is that the inner radius of the accretion disk $R_{in}$ can be identified with the radius of the innermost stable orbital (ISCO) $R_{ISCO}$, due to the fact that the inner radius of the accretion disk is in a constant state without changing with time in the experiment [4] and Jeffrey E. McClintock et. al. [5] obtained the result that $R_{in}$ can be approximated with $R_{ISCO}$ according to GRMHD simulation. The second thing is that there is a very direct relationship between the spin parameter $a$ and the radius of ISCO [6]:

$$r_{ms} = M\{3 + Z_2 \mp [(3-Z_1)(3+Z_1+2Z_2)]^{1/2}\},$$
$$Z_1 = 1 + (1 - a^2 / M^2)^{1/3}[(1 + a / M)^{1/3} + (1 - a / M)^{1/3}],$$
$$Z_2 = (3a^2 / M^2 + Z_1^2)^{1/2}$$

where $r_{ms}$ is the radius of critical stable orbits which is what we call the innermost stable orbital radius $R_{ISCO}$, $M$ is the mass of the central object. Thus, measuring the spin can be done by measuring the accretion disk's inner radius, and according to equation (1) the relationship between them is shown in figure 1.

The black hole's accretion disk dissipate energy through thermal radiation, which is observed soft X-ray bands in stellar black holes and optical/UV/EUV bands in supermassive black holes [7]. In addition, non-thermal radiation components can also be observed. This includes the power law spectrum generated by the inverse Compton scattering of the thermal radiation with the high temperature electron in the corona close to the accretion disk, including the reflection spectrum generated by the hard x-rays from the corona radiating back to the accretion disk. The reflection spectrum contains fluorescence lines, absorption edge and Compton hump, in which the iron line is the most remarkable feature owing to its abundance and fluorescence yield.

However, this reflection spectrum is greatly widened and skewed due to the influence of the Doppler effect and the relativistic effect, and the closer it is to the horizon, the greater the variety [8]. These effects provide us with an important reference for measuring the innermost stable orbit. Thus, the innermost stable orbit’s radius $R_{ISCO}$ can be estimated by the analysis of the emission iron-$k\alpha$ line, then the spin can be measured.
Figure 1. The relationship between \(a_*\) and \(R_{ISCO}\) is shown.

When the disk radiation is close to the Eddington luminosity, the greater the mass \(M\), the lower the temperature \(T\) \((T \propto M^{-1/4})\). For the accretion disk of the interstellar black hole, the temperature is about 10\(^7\) K, and the corresponding thermal radiation is in the soft X-ray region. For the supermassive black holes in AGNs, the thermal radiation corresponding to their temperature is at the optical/UV/EUV bands [7]. Both types of black holes’ accretion disk radiation are called thermal radiation. However, in the observed spectral, a hard X-ray component can also be observed, which is nonthermal component, and its source must be some external structure other than the accretion disk.

3. Model of X-ray Reflection Spectrum

Before analyzing the broad emission iron-\(k\alpha\) line, we need to model the other components. In the observations of supermassive black holes in AGNs, we are going to model other four spectrum components: (i) one is the power law spectrum produced by the corona, (ii) one is the distant reflection generated by the low-velocity material, (iii) one is the absorption lines produced by photoionization cold gas, (iv) and the last is soft excess fitted by a blackbody or additional Comptonization component [7] due to the actual observation. In the observations of black holes with stellar mass in X-ray binaries, the fitting of the spectrum is similar to that of AGNs and even has better signal-to-noise ratio, but it requires an additional thermal emission since the accretion disk is hotter than the supermassive black hole’s. Moreover, in the previous fitting, the absorption component due to outflows will not introduce the broad-band curvature [7]. After completing the above model fitting, we can further analyze the remaining X-ray reflection components.

In 2005 Ross & Fabian proposed a reflection model, REFLIONX, that can be used for both general application as well as for measuring black hole spin [9]. And it uses the diffusion equation, which is widely used in the last decade, to solve the radiative transfer problem. However, this method can only provide a spectral fitting of an angle-averaged spectrum. Then, in 2014, J. García et al. proposed an improved model called RELXILL [10] which overcome the simplified treatment of the angular distribution of the reflected X-rays. This model is based on RELLINE, which simulates the relativistic components, and XILLVER, which simulates the non-relativistic components. RELXILL has been widely used to analyze the reflection spectra in X-ray binaries and AGNs recently.

In the reflection models, in addition to the spin parameter \(a_*\), there are many common and important parameters that we all need to understand. The parameters include ionization parameter \(\xi\), photon index \(\Gamma\), iron abundance \(A_{Fe}\), and the inclination of the orbit to our line of sight \(i\).

Ionization parameter \(\xi\) have a significant influence on the emission and absorption characteristics in the reflection spectrum as we fixing other parameters [9]: when the ionization parameter \(\xi\) is large (i.e. 104 erg cm.s\(^{-1}\)), the accretion disk’s surface layer is highly ionized, and the emission feature is
Compton broadening Fe Kα line with a peak at 7 keV; When the ionization parameter $\xi$ is small (i.e. 102 erg cm.s$^{-1}$), some lighter elements cannot be completely ionized, and we can recognize the Fe line at 6.4 keV mostly comes from fluorescence emission. For the photon index $\Gamma$, it can be found from the fitting that as $\Gamma$ increases, the iron Kα line becomes weak and the Lα line becomes very strong, which means that the ionization of the disk decreases with $\Gamma$. For iron abundance $A_{\text{Fe}}$, when it vary to only 0.2 times the solar abundance, the emission of Kα and K-absorption will become weaker than solar abundance; while when it becomes 5 times the solar abundance, some elements that could remain highly ionized to an equally great depth will become very strong (i.e. Fe Kα, Lα). For inclination $i$, it will affect the equivalent width of the spectrum that we observe. Because the photons produced by the iron atoms do not hit our observer directly but are deflected at an oblique angle resulting in additional absorption and scattering, the spectrum we observe becomes narrower. The bigger the inclination $i$, the greater the effect on spectral narrowing. Finally, for the spin parameter $a$, we want to measure, as the fitting value increases, the Fe K line is significantly widened, which can also be understood because a larger spin means that the black hole rotates faster, that is, the innermost stable orbit is closer to the black hole, which will cause a significant broadening of the spectrum due to the extremely large mass.

Since these parameters are sensitive to the reflection spectrum, it is necessary to make them vary during the fitting. The self-consistency is also required to be considered in the model. Then, we can measure the spin accurately.

4. Other Methods
Based on the influence of the black hole spin on accretion disk itself, we can also measure the spin by modeling its X-ray emission. This is called the continuum-fitting (CF) method. In this method, we also use the relationship between $R_{\text{ISCO}}$ and $a$, to measure the latter, and the former is also considered to be equivalent to the accretion disk’s innermost radius $R_o$. With CF method, the black hole’s mass $M$, our distance from the black hole $D$, and the inclination $i$ need to be measured in advance [11], then the spin can be measured precisely. However, when we measure the inclination $i$, we use the binary orbital inclination instead of it, which introduces a greater error to the spin measurement. Moreover, since the thermal radiation temperature of the accretion disk is negatively correlated with the central object’s mass, the thermal radiation of the accretion disk of the supermassive black hole in AGNs is in the optical/UV/EUV bands, so CF method cannot measure a wide mass span and can only be used for measuring the stellar black hole.

In recent years, the observation of gravitational waves [12] has also provided a new method to measure the spin of black holes. All three stages of a black hole binary system merger which are the inspiral stage, the merger stage and the ring-down stage could emit gravitational waves. [7]In the inspiral stage, two black holes revolve around the center of mass losing energy by emitting gravitational waves. In the merger stage, they emit strong gravitational wave due to the smaller distance between them and the rotation become faster. In the ring-down stage, they finally tend to be a single Kerr black hole due to large amounts of energy loss and emit different gravitational waves. Those gravitational waves, in principle, carry all sorts of information about the spin of the two black holes and the last Kerr black hole. Gravitational wave signals are very clean, and it is easier to use them to measure the spin than reflection spectrum if we have observed this signal. But the problem is that it is not easy to detect gravitational waves, which makes it difficult to do so. Another drawback is obvious: we can only measure the spin of binary black holes, but we could do nothing with supermassive black holes in AGNs.

5. Conclusion
Above all, the reflection spectrum has a lot of advantages in measuring the spin of black holes: (i) It can measure black holes with masses ranging from a few dozen solar masses to a million even 10 billion solar masses; (ii) It can also measure the inclination $i$ of the accretion disk while measuring the
spin [13]; (iii) And no additional parameters (i.e. L, M, i ) are required to be known in advance in the X-ray reflection method. (iv) Besides, the measurement of spin by reflection has inspired the study of neutron X-ray binaries [14].

But the measurement of spin by X-ray reflection spectrum still faces several challenges. In the observation, we need to choose the mode carefully to avoiding photon-pileup. In spectral fitting, we must fit every component. For example, the failure to fit Comptonized hard X-ray tail and the thermal radiation component of the disk will result in an error of the final measured spin. And in the final data processing, we must pay attention to that the error is affected by both the systematic uncertainty (the error from the reflection spectrum parameters) and statistic uncertainty (the error from the instrument), so we must pay great attention to the change of the error bar [7].

Now we need to make effort to overcome these challenges to get a more accurate spin, and we need to pay attention to the new implications of reflection measurement of spin, which may lead to more discoveries and challenges.

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