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A Deep Dive into Black Hole Spin Measurement Using Continuum Fitting

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Abstract: This paper explores the continuum fitting method for estimating the spin of stellar-mass black holes in X-ray binaries. By fitting the thermal emission created by the accretion disk to theoretical models, this method provides a precise and accessible way to estimate the spin of black holes. Key developments, including the use of KERRBB and SIMPL models, improve accuracy by accounting for disk structure and Compton scattering effects. This paper reviews recent applications of this technique and compare it to the X-ray reflection method, noting that continuum fitting is highly accurate for black holes with strong thermal emission. This paper also gives the new spin measurement of some black hole, especially the Cygnus X-1, that has the spin $a_* > 0.976$, but also use it to prove that the continuum fitting method which relies heavily on knowing the black hole's three parameters. Finally, this paper discusses both the advantages and challenges of this method, with an expectation of future improvements in modeling and observations that can expand its use.

Keywords: accretion disk, black holes, continuum fitting method, spin measurement.

1. Introduction

With the development of technology, people's understanding of black holes becomes deeper and deeper. In the black hole solutions of Einstein's equation have three parameters: mass M, angular momentum J and charge Q [1]. The angular momentum J can also refer to the spin a_*. As the equation shows the spin of the black hole is one of the most important properties. Therefore, finding a method to estimate the spin of black holes becomes significant.

The first viable method of measuring black hole spin was presented in 1989, with an emphasis on simulating the inner accretion disk's relativistically-broadened Fe K emission line [2]. This method marked a major breakthrough in black hole spin studies. However, it wasn't until 1997 that an alternative approach, known as the continuum fitting method, emerged as a viable technique for spin estimation [3]. Both methods have their strengths, but each is suited to different contexts and comes with distinct advantages. The reflection fitting method is more complex, but it is more applicable to supermassive black holes. However, the continuum fitting method is advantageous in its precision of the measurement and simplicity.

This paper will focus on the wide application of the continuum fitting method, discussing its advantages by analyzing the newest values of the spin of different black holes and analyzing its concepts behind the method. This paper will also explain the reasons which help this method to be advantageous in some ways.

The following structure of this paper will be, in Section 2, this paper will contain a literature review of some applications of this method. In Section 3, the paper will introduce how the continuum fitting method works. In Section 4, the paper will contain a part for results. In Section 5, the paper will discuss the advantages and disadvantages of the continuum fitting method compared to the other method. In Section 6, a conclusion will be made for the paper and the limitation of the study and the direction of future research will be proposed.

2. Literature Review

The continuum fitting method has undergone significant development, thanks to the contributions of numerous researchers. Initially, the method estimates the black hole's dimensionless spin parameter (a_*) and mass accretion rate ($\dot{M}$) by fitting the thermal continuum spectrum of a black hole's accretion disk to the relativistic thin-disk model. The foundation for this approach rested on the Novikov-Thorne (NT) model, which provided a relativistic framework for calculating the spectrum of radiation emitted by a thin accretion disk. This allowed for more precise spin measurements [4]. In addition, one of the most widely used tools in this method is the KERRB2 model, which integrates the strengths of two other models: BHSPEC and KERRBB. This combined model allows for direct fitting of both the black hole's spin and the Eddington-scaled luminosity (L/LEdd), while retaining the returning-radiation effects found in KERRBB. By capturing these features, the kerrbb2 model enhances the accuracy of spin measurements [4]. Besides, another important challenge addressed in the development of the continuum fitting method was the accurate modeling of the Compton component. Comptonization can distort the thermal spectrum, and early applications of the continuum fitting method struggled with this interference. However, the adoption of SIMPL models for the Compton component has enabled reliable spin measurements, even for spectra where Comptonization plays a significant role [5]. With these improvements, the continuum fitting method has expanded its utility, finding applications in a wide range of astrophysical contexts beyond its original scope [4].

3. Methodology of Continuum Fitting

The concept behind the continuum fitting method is based on the properties on the properties of the accretion disk around the black hole, by analyzing the thermal radiation from it. This method also relies on fitting the X-ray continuum spectrum of the accretion disk to theoretical models, in order to determine the spin [4].

Here are some key concepts behind the continuum fitting method: first, it's the thermal radiation from the accretion disk. The accretion disk around a black hole emits thermal radiation primarily in the X-ray spectrum. The disk is composed of gas that spirals inward toward the black hole, heats up due to frictional forces, and emits radiation with a characteristic blackbody-like spectrum. The temperature of the disk is highest at its inner edge, and this high-energy radiation is crucial for determining the properties of the black hole [4]. Second, the innermost stable circular orbit (ISCO) is the closest distance from the black hole at which material can stably orbit before falling in. The location of the ISCO depends on the black hole's spin with an inverse relationship: for a non-rotating black hole, (Schwarzschild black hole, spin parameter a_*=0), the ISCO is located at 6 gravitational radii ($r_g = \frac{GM}{c^2}^*$) which is farther out, while for a rapidly rotating black hole (KERR black hole), it is closer. Therefore, determining the ISCO provides crucial information about the black hole's spin [6]. Moreover, it is the spectral fitting. By observing the X-ray continuum spectrum of the accretion disk and comparing it to theoretical models, the location of the ISCO can be inferred. The models describe

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how the temperature distribution of the disk varies as a function of radius, and the spin of the black hole affects the temperature profile and overall luminosity. The observed spectrum is fitted to find the model that best describes the data, which in turn yields the spin [7]. Besides, input some certain parameters, such as the black hole's mass, the distance to the black hole, and the inclination of the accretion disk, are important in order to obtain the accurate measurement of the spin of the black hole [4].

*G is the gravitational constant; M is the mass and c is the speed of light.

4. Result

The continuum fitting method is particularly suitable for stellar-mass black holes in binary systems, where the X-ray emission from the accretion disk is bright and steady enough to allow detailed analysis [8].

This method creates an advantage on accuracy. Uncertainties in the source distance, black hole mass, and disk inclination are the main causes of mistakes in the continuum fitting approach; nevertheless, prior research has demonstrated that these errors appear to be minimal [9]. In addition, relying on the idealized Novikov-Thorne thin-disc model, the errors in the measured spin parameter using the continuum-fitting method are comparable to or smaller than the current observational uncertainties [10]. What's more, previous study shows that the continuum-fitting method is less affected by the presence of the iron line and other reflection features in the X-ray spectrum, which can complicate spin measurements. However, the authors show that excluding the energy range covering the iron Kα line and edge has a negligible effect on the spin results. Besides, the creation of SIMPL model offers a way to estimate the Compton scattering fractions on the spectra, which helps with the accuracy of the measurement for situation with high Compton scattering fractions, and which also helps to increase the application range of the continuum fitting method.

Table 1: Spin measured by continuum fitting method

Black hole	Spin	References
IC 10 X-1	$\mathbf{0.85^{+0.04}_{-0.07}}$	12
M33 X-7	$\mathbf{0.84 \pm 0.05}$	13
LMC X-3	$\mathbf{0.16 - 0.33}$	14
LMC X-1	$\mathbf{0.92^{+0.05}_{-0.07}}$	15
XTE J1550–564	$\mathbf{-0.11 — 0.71}$	16
Nova Mus 1991	$\mathbf{0.63^{+0.16}_{-0.19}}$	17
4U 1543–475	$\mathbf{0.43^{+0.22}_{-0.31}}$	18
Cygnus X-1	$\mathbf{> 0.976}$	19

Note. The listed spins are all at the 90% level of confidence.

The Table 1 represents the black hole spin measurements estimated by using the continuum fitting method. For instance, spins for IC 10 X-1 and M33 X-7 are high, $0.85^{+0.04}_{-0.07}$ and 0.84 ± 0.05 , respectively, while LMC X-3 shows a relatively lower spin range of 0.16–0.33. In addition, XTE J1550–564 shows a spin between -0.11 and 0.71 which conclude that in some certain circumstances it is spinning in a negative direction. Also, Cygnus X-1's spin is very close to 0.998 confirming that the system contains an intense Kerr black hole [19].

5. Discussion

For stellar mass black holes in X-ray binaries, the continuum fitting approach is frequently used. It depends on the accretion disk's thermal emission, whose high-energy is radiation is essential to figure out the black hole's spin[4], and ISCO, the radius of it depends on the black hole spin, is also important to the measurement [6]. It is required to fit into the thermal spectrum [7] and provide the black hole's mass, distance and inclination of the disk, the spin can be inferred with high precision [4]. Therefore, the simplicity of the method, involving fewer assumptions about complex disk physics, allows for a direct and reliable measurement of the spin. However, the continuum fitting method also shows a very apparent disadvantage in this case. It is that this method relies too much on the three parameters—mass, distance and the inclination of the disk—so that one single change in the values of any of the parameters will cause the re-measurement of the spin. For example, in the case of Cygnus X-1, some small changes in the parameters can cause a re-evaluation of the spin [19].

In contrast, the X-ray reflection method is commonly used for both stellar-mass and supermassive black holes in active galactic nuclei (AGN). By modeling the broadening and distortion of the iron Kα emission line and the full reflection spectrum, which are shaped by relativistic effects near the black hole, this technique provides an indirect way to measure spin. While more complex and dependent on various disk properties such as ionization and geometry, the reflection method does not require prior knowledge of the black hole's mass or distance. This makes it ideal for studying AGNs and black hole systems where these parameters are uncertain [11]. Besides, referring back to the spin measurement in Table 1, some black holes, such as 4U 1543–475 and LMC X-1, both black holes have the same estimation on spins from the continuum and reflection fitting method, which shows that the continuum fitting method is quite accurate. However, most of the black holes have the spin measurement by only one of the methods, such as IC 10 X-1 and M33 X-7, which is because two of the methods fit into two completely different circumstances. It is better to use the continuum fitting method for the spectra with strong thermal emission; however, it is better to use the reflection fitting method for spectra with strong reflection emission.

6. Conclusion

The continuum fitting method has emerged as a powerful and accurate technique for determining the spin of stellar-mass black holes in X-ray binaries. By analyzing the thermal emission created by the accretion disk and leveraging well-established models, this method offers a reliable way to calculate black hole spin. The method's simplicity and accuracy are clear advantages, such as black holes IC 10 X-1 and M33 X-7, whose spin measurements are $0.85^{+0.04}_{-0.07}$ and 0.84 ± 0.05 , having very low errors, but the method's dependence on accurate measurements of key parameters also brings some disadvantages. But moving forward, further advancements in modeling and observational techniques may help address the limitations of this method, while expanding its application to a broader range of black hole systems. Both the continuum fitting and reflection fitting methods complement each other, contributing to our growing understanding of black hole physics!

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