Stellar-mass Black Hole Spin Measurements and its Implementation

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Abstract. The spin of the black hole is one of the deterministic qualities for itself, providing us with the knowledge of its birth and evolution. In this review, I described two kinds of the spin measurements, respectively based upon electromagnetic waves and gravitational waves, and discuss the meaning for the black hole spin evolution indicated by the spin results measured by these methods. We find that for X-ray binaries, the spin results are much bigger than those results for natal spin, and for binary black holes the spin result are much smaller than those in X-ray binaries, which may be resulted from their different evolutions. For binary black holes detected through gravitational waves, formation channels of the binary systems are essential for interpreting spin results in these binary systems.

1. Introduction
A black hole is an astrophysical object that has the strong gravitational pull, which forms the event horizon. Inside the event horizon, even the light itself cannot escape. Because of the strong gravitational pull, materials such as gas and particles near the black hole are dragged into the event horizon. This event horizon, a virtual boundary, makes the black hole, among all astrophysical objects, the simplest objects in the universe, only defined by its mass and angular momentum. The black hole with mass M forms a gravitational radius:

$$r_g = \frac{2GM}{c^2}$$

where c is the speed of light and G is Newton’s constant of Gravitation.

Similar to mass, which is connected with the gravitational radius $r_g$, the angular momentum, or so-called spin, also retains information of the black holes, such as evolution process of black holes, and powering process for the relativistic jets.

For the evolution process of the black hole, especially its spin, started from the gravitational collapse of the star, a nonzero spin is assigned to the black hole. The initial spin state depends upon the angular momentum of the original star and the magneto-hydrodynamics (MHD) of core-collapse in evolved, rotating stars. Black hole spin will also change due to a major merger, where a black hole merges with another comparable black hole, and a minor merger, where a black hole merges with smaller companions. Moreover, the spin can grow with accretion of the nearby materials, such as plasmas and gas [1].

For the powering process of the jets, the spin energy is extracted by electromagnetic field to transmit the energy to the relativistic jets [2].

Suppose a black hole with the angular momentum J and mass M, we can define an unitless “spin parameter” by

$$a_s = \frac{cJ}{GM^2}$$
In order to understand the spin, measurements of the black hole’s spin are the primary requirement. There are two kinds of the spin measurements. The first one is measuring spin by electromagnetic wave. This kind of the spin measurement, such as continuum fitting and X-ray reflection method, collects the electromagnetic wave radiated from the black hole’s accretion disk to gain knowledge of the black hole’s spin.

The second kind of the method is through the gravitational wave to measure the spin. In this method, we collect the gravitational wave emitted by the black hole and analyse its waves parameters \(\{\omega, \tau\}\), where \(\omega\) is the vibration frequency and \(\tau\) is the radiation-reaction-induced damping times, to calculate the black hole’s parameters \(\{M, a^*\}\) \[3\].

In the later sections, I introduced the two spin measurements, electromagnetic and gravitational measurements in section 2, and discuss the relation between spin and formation of the black hole in section 3. And I make a conclusion in section 4.

2. Spin and its measurements

2.1. The spin measurements based upon Electromagnetic measurements (X-ray)
In the electromagnetic spin measurements, the basic assumption is that the accretion disk remains geometrically-thin, optically thick, and radiatively efficient down to the ISCO \[4\]. The mechanics of this measurement is based upon the black hole’s accretion disk’s differential rotation, which will generate the heat from friction between materials near the black hole. And the temperature of the heat corresponds to the electromagnetic wave in the X-ray range, allowing us to analyse the X-ray spectrum to measure the spin. There are three compositions of the X-ray spectrum collected from the electromagnetic measurements: (1) the thermal component, (2) the power-law component, and (3) the reflection component, including the relativistically broadened Fe K\(\alpha\) line \[5\].

There are two major techniques using the electromagnetic wave: (1) Continuum fitting method, proposed by Zhang et al in 1997 \[6\], and (2) X-ray reflection method, the first practical approach suggested by Fabian et al (1989) \[7\].

Firstly, in the Continuum Fitting method (CF), one should fit the thermal continuum spectrum of a black hole’s accretion disk to the Novikov and Thorne’s relativistic thin disk to get the radius of the inner edge of the disk, which can be identified with the radius of the innermost stable circular orbit \(R_{\text{ISCO}}\). The \(R_{\text{ISCO}}\) is linked with the spin parameter \(a^*\) \[8\].

Secondly, with the X-ray reflection method, black-hole spins among range of mass, from stellar-mass black holes in X-ray binaries to the supermassive black holes in active galactic nuclei (AGN), can be measured. In this method, data of the black hole mass and its distance are not required. Neither do we require knowledge of the accretion disk inclination, since X-ray reflection spectroscopy measures the inclination simultaneously with the black hole spin. The power-law model can fit the X-ray continuum in the 2-50 keV range very well. In the range \(\hbar \nu \ll E \ll kT\), the most common and obvious features observed in the spectra are (1) a narrow iron-K\(\alpha\) emission line at 6.4 keV, and (2) absorption by cold and photon-ionized gas. Due to these features, we need to add some models and parameters to the power-law spectral model: (1) a model of cold, distant X-ray reflection, (2) a successive absorption component, (3) the ionization parameter, (4) column density, and (5) phenomenological component \[4\].

2.2. The spin measurement based upon gravitational wave
With the gravitational waves emitted by a merger of the black-hole binary system observed by the advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO), the measurement of black-hole spin based upon gravitational waves became an alternative.

There are three distinct stages to the merger of a binary black hole system: (1) the “in-spiral” stage, where the two black holes orbit around their shared centre of mass, emitting gravitational waves, (2) the “merger” stage, where the two black holes merge together to produce gravitational wave signals, and (3)
the “ring-down” stage, where the remained single black hole radiates the gravitational wave signals and settles down to a Kerr black hole [8]. By analysing the gravitational waves emitted during the “in-spiral” stage, we are able to calculate the black-hole parameters \( M, a^* \) by the wave parameters \{\omega, \tau\} [3]. The spin of the remained single black hole during the ring-down stage can also be examined through the gravitational waves. However, with the limits of current technological sensitivities, the ring-down radiation cannot be detected. But we can deduce the spin of the single black hole by putting parameters gained from the “in-spiral” waves into the computer simulations [8].

There are several independent parameters that determine the gravitational-wave signal radiated by a binary black hole system: (1) the black-hole masses and the black-hole spin vectors, (2) the inclination and the phase of the observer in the orbital plane, (3) the sky location of the binary system, (4) the polarization angle of the gravitational wave, (5) the luminosity distance to the binary, and (6) the time of arrival of the gravitational wave at the detector. To get these parameters, Bayesian inference algorithms and the accurate theoretical predictions of the gravitational-wave signal are requisite [10].

3. Discussion
A non-rotating black hole must accrete its initial mass to achieve higher spins. [11]. For a black hole in an X-ray binary system, accretion does not significantly affect the spin of the black hole, since a low-mass star cannot give sufficient mass and a high-mass star cannot give sufficient mass in its short lifetime. Thus, we have the conclusion that the spin of stellar-mass black holes remains constant after its birth [12].

There are some physical process for the black hole spin formation: (1) initial nonzero spin, endowed by the progenitor star during its gravitational collapse, (2) material integration to the accretion disk, which may spin up the black hole spin, and (3) black hole’s merger, which may increase the black hole spin and mass ratio above 0.8, or spin-down the black hole instead [13, 11, 1, 14, 15].

In the Table 2 of Reynolds (2020) [16], the spins of majority of the binary system are bigger than 0.7 and the smallest spin is \( a_* = 0.12 \pm 0.19 \) of AO620-00 by CF measurement. In this table, we can find that the most of them have a spin much greater than 0.03, which is the maximum value for the natal spin parameters of neutron stars [12]. This shows difference in the core-collapse supernovae that have produced the black hole and neutron star populations. One hypothesis for the case of neutron stars is that either a magnetic propeller mechanism or R-mode instabilities might lead to significant reduction in the angular momentum of the rapidly-rotating compact objects [4, 12]. Also, most of the black holes measured in the Table 2 of Reynolds (2020) are endowed with positive spin, meaning the direction of black-hole spin is in agreement with the direction of accretion-disk spin [9].

For the spin of GRO J1655-40, there is a controversy in results of spin shown by Shafee et al. (2008) and Reis et al. (2009). In the paper of Shafee et al. (2008), the spin result measured by the CF measurement is in the range of 0.65–0.75 [17], whereas 0.94 < \( a_* < 0.98 \) measured by the reflection method in the paper of Reis et al. (2009) [18]. This controversy results from the CF’s spin-orbit assumption that the plane of the inner X-ray emitting portion of the disk is aligned with the binary orbital plane [9], and from the source distance \( D \approx 3.2\pm0.2 \) kpc, which, however, is shown by Foellmi (2009) that the source distance is most likely to be less than 2 kpc [19]. When this distance is used, the spin parameter \( a_* > 0.91 \), which is in agreement with the spin result from reflection method [18]. Furthermore, the spin of GRO J1655-40 is examined by Stuchl et al. (2016) using the epicyclic resonance model, which is also consistent with the result shown by the reflection method [20].

For binary black holes detected by the gravitational-wave method, there are symmetric black-hole binary systems and asymmetric black-hole binary systems. For symmetric black-hole binary system, GW150914, with a merger of a 35\(^{+5}_{-3}\)\(M_\odot\) black hole and a 30\(^{+3}_{-1}\)\(M_\odot\) black hole, has an effective spin \( \chi_{eff} = -0.04^{+0.14}_{-0.16} \), indicating that this system does not contain rapidly rotating black holes that are aligned or anti-aligned with the orbital axis [8]. There are several formation channels that this binary system may evolved through: (1) the dynamical formation in a dense stellar environment, (2) the isolated binary evolution, or (3) chemically homogeneous evolution in close tidally locked binaries. All these formation channels are consistent with the event of GW150914 [10]. Also, for the spin evolution of this...
binary system, GW150914, B. P. Abbott et al. (2016) showed that the initial spin is consistent with the merger spin by numerical relativistic simulation of 1000 distinct configurations from the precessing effective-one-body nearby [10].

For asymmetric black-hole binary systems, the binary black hole merger of GW190412, with $M_1 = 29.7_{-5.3}^{+5.0} M_\odot$ and $M_2 = 8.4_{-1.6}^{+1.8} M_\odot$, gives an effective spin $\chi_{\text{eff}} = 0.25_{-0.11}^{+0.08}$ and the precession spin $\chi_\rho = 0.30_{-0.16}^{+0.19}$. Through LIGO-Virgo Consortium analysis, a primary black hole spin is of $a = 0.43_{-0.26}^{+0.16}$[16]. In Mandel et al. (2020), they argued that within the context of isolated binary evolution, the primary massive black hole is born with negligible spin with a secondary massive black hole endowed with a high spin between 0.66 and 0.99 [21]. However, Zevin et al. (2020) examined data based upon different spin priors and proposed that the primary black hole may have a moderate spin. In brief, it is still equivocal whether the moderately spinning primary interpretation or highly spinning secondary interpretation fits the GW190412 [22, 16].

In these binary systems, we note that symmetric black-hole binary systems are detected during the first and second LIGO-Virgo observing runs, constrained by the effective spin $\chi_{\text{eff}}$. However, only by the mild information of the spin, we cannot determine the particular formation channels for these symmetric systems. For the asymmetric black-hole binary systems detected during the third runs of LIGO-Virgo observing and constrained by effective spin $\chi_{\text{eff}}$ and $\chi_\rho$. In all these binary systems, spin priors’ assumptions — uniform priors on the two component masses, uniform prior on the magnitude of the two dimensionless spins, and an isotropic prior for the directions of the two spins — are important in reaching astrophysical conclusions about the spin results detected.

4. Conclusion
In this paper, we have reviewed the two major spin measurements based upon electromagnetic waves and gravitational waves. Through methods based upon electromagnetic waves, we present a hypothesis that either a magnetic propeller mechanism or R-mode instabilities might lead to significant reduction in the angular momentum of the rapidly-rotating compact objects (Section 3), from the spin results collected in Table 2 of Reynolds (2020). However, there are still some controversies between CF method and X-ray reflection method due to the limitations of techniques. The future of black hole spin is bright. Due to the high-throughput X-ray observatories such as Athena, XRISM, and etc, more precise and accurate spin measurements based upon

X-ray reflection, X-ray iron line, thermal continuum fitting, and quasi-periodic oscillations will be implemented and improved [16].

Also, spin results from gravitational-wave method may indicate the formation channels of the binary black holes. However, due to less accurate models and methods applied in the gravitational-wave method, there are still some uncertainties about the spin priors. But in the future, as the gravitational-wave observatories in high-throughput, more accurate methods and models, and more sensitive techniques will be developed and implemented.

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