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Misalignment of jet, orbital plane, and accretion disk observed in black hole binaries

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Abstract. Black holes are interesting objects and prove to be the leading edge of testing and verifying of our understandings in gravity. Among some of the most sought after quantities is the spin of the black hole: it is closely related to how the black hole system behaves. Various attempts have been made to derive the spin of black holes, in which the orientation in space could be deduced using the spectrum produced by the accretion disk, observation of the jets produced by black holes, and calculation of the orbit of black hole binaries using light and velocity curves. These observations, however, can sometimes lead to disagreeing results. In this paper, conflicts of the orientations of the spins of black holes measured using these different methods are presented. Sources including XTE J1550-564, V404 Cyg, and V4641 Sgr display misaligned accretion disk with orbital plane and/or jets. Explanations of how such misalignments could arise are also given, including warped accretion disks and precessing jets.

Keywords: black hole physics, accretion disks, X-ray binaries

1. Introduction

Black holes are surprisingly simple objects in terms of their inherent characteristics. A black hole can be described by three numbers: mass, angular momentum (spin), and electric charge. In addition, it would be easy for a black hole to neutralize the charge via absorption of free charged particles in the environment, so the full set of inherent properties further reduces down to the mass and spin. It is therefore of particular interest to determine those two properties via many ways, from dynamics of orbiting objects to analysis of spectra produced by black hole system. There are also multiple reasons of studying black holes: they are the most compact objects with the most extreme gravitational environments, making them excellent places to test our understanding of both macroscopic and microscopic interactions. Black holes are also important objects in terms of cosmology and structure of galaxies, as they mark one of the final destinies of massive stars and are found in the center of many galaxies. They also make for good places to test our current models of magnetohydrodynamics.

The focus of this paper would be the discrepancy between measurements of various components of black hole binaries that are commonly thought to be somewhat representative of the spin orientation of the black hole. These components include the jets powered by black holes, the orbits of companions in black hole binaries, and the accretion disk surrounding the black hole. Measurement of the orbits and the jets are relatively easier to understand: the apparent inclination of the companion could be determined by observation of the dynamics of the binary system, and jets are usually composed of particles at relativistic speeds that make them fairly pronounced on a wide range of wavelengths. Fe K line fitting could also independently yield a value of accretion disk inclination.

A somewhat common notion about these components is that they roughly align with each other: jets are mostly powered by the infalling matter and the spin of the black holes themselves, accretion disks are “torn” to align with the spin of the black holes [1], and orbital angular momentum should roughly coincide with that obtained from the aforementioned phenomena as the black holes in binary systems are usually young and natal ticks experienced in supernovae explosions are usually taken to be not too significant to the resulting black holes. However, there are observations in which two or three out of these phenomena do not align with each other, which may hint that there could be some lack of understanding about black hole binaries [2]. The study of such discrepancy could also lead to further understanding of our current theories of supernova explosion and accretion, as the natal kick experienced during the supernova explosion could be responsible for the misalignment between black hole spin and angular momentum of the system, while continued accretion could increase the spin of the black hole and change the orientation of the spin.[3]

This paper is structured as follows: in section 2, measurements of the inclinations of accretion disks, jets, and orbits of black hole binaries are introduced. Instances in which the accretion disk and the orbit/jet misalign are discussed in section 3, with some explanations on how these misalignments are produced and what could be sought after in the future given in section 4. The conclusion to the paper is given in section 5.

2. Literature Review

2.1. Measurement of Black Hole Accretion Disk Inclination via Fe K Line

There are multiple components in the X-ray spectrum of a black hole, and one that proves to be practical for our cause is the Fe K line. To be more specific, the measurement is conducted by observing the Fe Kα line at around 6.4 keV, which is used instead of the Kβ line as the latter is weaker in amplitude [4]. The black hole accretion disk could be roughly described as a black-body, which radiates photons at a relatively low energy. These “soft” photons have a chance to enter the hotter corona and, after multiple inverse Compton scattering events, come out of the corona as “hard” (high energy) X-ray photons. These photons subsequently illuminate the accretion disk [5,6], causing Compton scattering again with the Fe atoms and ejecting electrons from the K-shell (innermost shell, n=1) of the atoms. An electron from the L-shell (n=2) could then fill the empty spot, and has some chance to release the energy in the form of an emission line photon.

The Fe Kα line produced by black holes does not show up as a thin peak; due to the fact that the atoms that produce the florescent line are in the spinning accretion disk and are under the influence of the black hole, the Fe Kα line is distorted due to multiple factors. These include Newtonian effects due to the Doppler shift, the special relativity effects including transverse Doppler shift and beaming, and general relativistic gravitational redshift. The distortion of the Fe Kα line could be modeled, and the line broadens in high energy regions with increasing inclination [7]. The Accretion Disk inclination obtained by this method is commonly thought to be representative of the black hole’s spin inclination, as it is generally assumed that the accretion disk could produce such florescent line all the way down to R_{ISCO} (radius of innermost stable circular orbit), after which the material plunges ballistically into the event horizon [8]. At such a small radius, the accretion disk is thought to align with the black hole’s spin due to general relativistic frame-dragging.

2.2. Measurement of Black Hole Jet Inclination and Binary System Orbital Inclination

We could also measure the inclination of jets produced by black holes. Jets are commonly thought to be produced using the energy of the black hole spin and the momentum of the infalling material [9], and they are composed of particles at relativistic speeds travelling up to thousands, if not millions, of parsecs and are evident on a broad range of wavelengths. Once we have measured the proper motion of the condensations caused by jets on, say, radio frequencies, the inclination could be solved using [10]

$$\mu_{r,a} = \frac{\beta \sin\theta}{1 \pm \beta \cos\theta} \cdot \frac{c}{D} \quad (1)$$

where $\mu_{r,a}$ stands for the receding and approaching proper motions, c is the speed of light, D is the distance to the source, and θ is the angle with respect to the line of sight.

Measurements of black hole binary orbital inclination are also taken out to ascertain the inclination of the black hole spin. The orbital inclination could be obtained using analysis of the system's dynamics, and many believe that this inclination is also somewhat representative of the inclination of the black hole spin, with the reason being explained later in section 3. Such measurements are usually taken out using the light curve and the velocity curve of the binary system, which are fed into a dynamical model in which free parameters like inclination and masses could be fitted.[11]

3. Categories of Misalignment

In this paper, the misalignment of the accretion disk, jet, and orbit is split into two cases for further discussion, namely the misalignment of the accretion disk with the jet and that of the accretion disk and the orbit. The underlying argument is that Fe Kα line probes the disk that is closest to the black hole, and is thus the one that must align with black hole spin in principle.

3.1. Discrepancy between Orbital and Accretion Disk Orientation

Black hole binary XTE J1550-564 is an example where the accretion disk does not align with either jet or orbit. Since it has been shown that the jet and the orbit of the binary system agrees well with each other [12], studies of the X-ray spectrum of the system have been carried out to see if modeling of the spectrum gives a similar result. However, the reflection spectrum from the same source has been collected and analyzed, and using simultaneous modelling of the data collected by RXTE and ASCA, it has been shown that the best fit of the spectrum produces an accretion disk at an inclination of $i = 39.2^{+0.9}_{-0.9}$ degrees. The inclination of the accretion disk is well restricted to ±1° at 90% confidence level, as the source was luminous and the relativistic broadening effect was fairly pronounced [2]. Combined with the orbital measurement of $i = 74.7°$ [11], this leads to a clear misalignment. This misalignment could hint that the black hole spin does not align with the system at formation, and the low mass of the companion of ∼ $0.3M_\odot$ means that even with efficient transfer of angular momentum in the form of, say, advection-dominated accretion flow, there is not enough matter to significantly change the orientation of the spin of the black hole such that it aligns with the orbit. This perspective is further aided when considering the mass of the black hole is significantly higher at ∼ $9M_\odot$.

Misalignment of the jet produced by XTE J1550-564 with its modeled accretion disk has also been observed, with the angle of misalignment also around 25°. The inclination of the jet produced by the system is ∼ 71° [12]. This poses a more challenging question, as it is commonly agreed that the jets produced by black holes are ejected around their poles and are thus representative of the orientation of their spin, while the accretion disks are also forced to align with the black hole spin at small radius. So, both the accretion disk and the jet should agree as they are aligned with the spin. In addition to this, some models show that the dominating power of the jet could be derived from the momentum of the infalling material, especially for the case of this black hole binary where the spin parameter of the black hole is determined to be around 0.5 [13-15]. For such a black hole with only moderate spin, energy provided by the infalling material dominates the energy extracted from the black hole spin when it comes to driving jets [9]. This means that not only should the accretion disk and the jet align due to the fact that they are both affected by the spin of the black hole, they are also directly related as one partially drives the other and the angular momentum information from the material in the accretion disk should be inherited by the jet. So there exists a contradiction between our current understanding and observation of XTE J1550-564: both spin of the black hole and the momentum carried by the infalling material require that the jet aligns with the accretion disk. Although the observed jet does not originate close to the black hole, meaning that there could be other physical processes that alter the orientation of the jet and it is not necessarily solely determined by the accretion disk and spin of the black hole, it

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is still worthwhile to consider the case where the jet could actually be traced back to close to the black hole.

One possibility of the large disagreement of the accretion disk orientation with the orbit and the jet of the system could be that the fitted model using X-ray spectroscopy is not very sensitive to the inclination of the accretion disk. However, this situation has been already contemplated, and if the inclination is changed to $\sim 75^{\circ}$, the value given by the orbit and the jet, a vastly increased fit parameter is observed, $\chi^2_{\nu} \sim 2$ [2]. This result is almost twice that of the fitted model, and a systematic deviation of $\Delta\chi$ could be seen around 6 and 10 keV. This means that the model is sensitive to the inclination of the accretion disk and it is thus not very likely that the fitting process lead to the observed misalignment.

It should also be mentioned that XTE J1550-564 is not the only system in which misalignment between the accretion disk, jet, and orbit could be observed; it is chosen to be discussed in further detail as its X-ray spectrum, jet, and orbit have been studied more thoroughly. V404 Cyg and V4641 Sgr are other examples of such disagreement; orbital estimations for these black hole binaries differ from the results of reflection spectroscopy by some $\sim 40^{\circ}$.[16,17]

Such misalignment is also not restricted to X- ray binaries; it is also postulated for AGN sources. For instance, misalignment of $\sim 60^{\circ}$ between the accretion disk and the jet of M87 is possible.[18]

4. Discussion

It has been a long standing and common assumption that the accretion disk and jet should be good indicators of the spin of the black hole. The relativistic frame-dragging effect experienced by the infalling matter close to the black hole means that the accretion disk should align with the black hole (at least the part that is sufficiently close to the black hole) [1], and numerous models and simulations show that jets are likely to be powered by the magnetic field in the accretion disk, which collimates part of the matter around the black hole to be ejected at the poles and could draw a significant portion of the driving energy from the spin of the black hole [9]. This means that the jet should also be aligned with the spin of the black hole as it inherits some of the information of the spin.

The relationship between the black hole's spin orientation and the orbital angular momentum orientation of the binary is not as direct. Although binary systems usually see alignment of spin of individual celestial objects with the orbital angular momentum, it is not necessarily true for every system. Continued accretion of the black hole could also force the spin of the black hole to align with the orbit of the system, as the infalling matter generally follows the orbit of the binary and carries the corresponding angular momentum into the black hole.

However, the dynamical time scale of such alignment is still not very certain and in some binary systems where the companion star of the black hole is massive, we could be sure that accretion has caused little deviation in the spin of the black hole for the age of the system is relatively young.

4.1. Validity of the Observations

It is unlikely that the observations of the reflection spectroscopy, the orbital dynamics, and the jet are erroneous. All of the cited measurements of the trio of XTE J1550-564 all use data that is taken over a period of months, and it is unlikely that mistakes were made during data reduction and analysis.

It is, however, possible that some assumptions made when analyzing the data is not quite right. To begin with, it has been reported that the iron abundancy deduced from the reflection spectrum produced by the system is abnormally high. This means that some assumptions that go into the components of the model may need correction, as the higher than normal abundancy could mean that the disk is unusually dense. In addition to this, the accretion disk of the system may not necessarily be geometrically thin and optically thick, making the modelling itself less meaningful as the inclination parameter would be fitting some artifact, though this is not very likely when the good fit parameters of the model is taken into consideration. The profile of the reflection spectrum may also be altered by other processes that are thus far not known.

If the accretion disk of XTE J1550-564 is not geometrically thin, another possibility arises in addition to the inclination parameter fitting some artifact: the Fe Kα line could also be obscured partially by the

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accretion disk itself as the disk is optically thick. This would mean that we are only observing part of the Fe Kα line produced in the region closer to us and this situation would further reduce the validity of the observation.

4.2. *Mechanisms that could Lead to the Misalignment*

Assuming that the observed misalignment is real, there are a couple of ways to explain this somewhat surprising misalignment.

A very straightforward explanation would be the accretion disk is distorted or warped. This situation could be created as the outer accretion disk inherits the orbital angular momentum carried by the infalling matter, and the inner accretion disk is forced to align with the spin of the black hole. The outer region of the accretion disk barely contributes to the measurement of the inclination as it experiences little general relativistic effects, so what we're seeing is the inclination of the inner accretion disk. The black hole binary system could have the orbit and the black hole spin misaligned due to the natal kick during the formation of the black hole, and continued accretion may not thus far change the black hole spin to the extent that it fully aligns with the system, since the timescale for such correction is on the order of the binary system lifetime.[16]

One additional advantage of the warped disk explanation would be that the jet could derive the vast majority of its power from the outer accretion disk, whose signal in X-ray is weak and thus has little effect on the inclination obtained by fitting the X-ray spectrum from the source. If the transient jet observed is actually powered by the outer region of the accretion disk, it would not be a surprise that it aligns with the orbit of the system: the outer accretion disk inherits the orbital angular momentum from the material contributed by the companion through the Roche lobe. This scenario is also compatible with the observation that the jet originates relatively far from the black hole.

Another possibility is that the jet of the black hole precesses over time and this leads to the observed misalignment. Both a massive companion and Lense-Thirring precession could lead the jet to deviate from the spin orientation of the black hole; such precessions could be readily observed in AGN systems [19]. Although the first case is not likely from the dynamics analysis, the latter could be the reason of the observed misaligned jet and accretion disk. However, this explanation could also face some difficulty as no significant variability is observed on the transient jet produced by the system.

4.3. *Future Observations*

The observed misalignment of the accretion disk, orbit, and jet in XTE J1550-564 could have implications in the study of black hole binaries, especially if it could be proven if the misalignment originates from our assumptions or the system indeed behaves in this way. A natural next step would be to select black hole binaries whose accretion disk, orbit, and jet could be observed with reasonable uncertainty to see if the pattern seen in XTE J1550-564 is infrequent.

To ascertain what causes the observed misalignment via observation would also be challenging. Since it is impossible to resolve black hole binaries in the foreseeable future, the measurement of the inclination of the accretion disk would still rely on modeling and thus it would not be viable to tell if the assumptions that go into the model are erroneous. It is, however, maybe possible that some new models would be able to extract the inclination of the outer accretion disk to verify the possibility of a warped disk mentioned in the previous subsection. Observations could also be conducted on jets produced by black hole binaries to see if there is a significant jet precession contribution to the misalignment.

5. Conclusion

The misalignment of the accretion disk, orbit, and the jet produced by black hole binaries is discussed in this paper. Some instances of black hole binaries where such misalignment could be observed is also provided, with XTE J1550-564 being the most notable one as there has been considerable effort to measure the aforementioned quantities of the system and the angle of misalignment is large; it is also one of the few systems where the modelled accretion disk does not align with the jet. Some possible explanations of why we are observing such misalignment is subsequently given, including warped disk and precessing jet. Such observation of the misalignment of accretion disk, jet, and orbit means that further discretion should be taken when assessing the orientation of the black hole spin, and maybe some of the assumptions on how black hole binaries behave should be reconsidered. In general, it would be desirable that more attention be paid when measuring the accretion disk, jet, and orbit inclinations of black hole binaries in the future to see if the misalignment occurs only in a fraction of the systems, or it is indeed a prevalent phenomenon that requires more effort at interpreting what it hints.

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