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Variability spectra of orbiting blobs around a black hole

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Abstract

Variability power spectra of collective orbiting blobs on an accretion disk around a black hole are investigated by a full relativistic approach. The resulting variability spectra are characterized by a power-law with flattening frequency at its lower end and a drop-off frequency at its higher end, both corresponding to the borders of blob distribution on the disk. The frequencies are intrinsic to all sources with an accretion disk around a black hole, independent of either the specific property of the disk or the nature of the blobs. The drop-off frequency can be an important clue in determining the mass of the central black hole, and may also be taken as evidence for the relativistic rotation of an accretion disk around a black hole.

1. Introduction

We present a study of variability from blobs orbiting a black hole, using a fully relativistic approach. An accretion disk around a black hole is subject to many kinds of instabilities (e.g., thermal and viscous instabilities) and some hydrodynamic features (e.g., magnetic flares and vortices). Therefore, its innermost part should not be smooth and steady, instead, it is “patchy” and “noisy”. This scenario is supported by the observed chaotic X-ray and UV light curves of active galactic nuclei and Galactic black hole candidates. The fluctuations of the disk can be well approximated by coherent corotating blobs or “spots”. The term *blob* has different meanings. It can be a vortex, a magnetic flux tube, a clump of matter with high density or even a small star. All can be “hotter” or “colder” than the background. Their size, life time, and brightness distribution are directly linked to the physics of accretion disks, although the relevant theory is not yet available.

One of the main observable effects of these blobs is the variability introduced to the observed signal, especially in the X-ray and UV bands originating from the innermost region of an accretion disk. First, the non-uniform brightness of the blobs and their different life time generate a “flickering” in the observed energy flux. Variability of this type is intrinsic to the source. Second, the blobs are close to the black hole and rotate around it with their Keplerian velocities being very high (several tenths of the speed of light). As long as the

orbits are not face-on, the Dopler effect modulates every individual flare as the blobs orbit the black hole and introduce (orbital) frequency-dependent variabilities in the signal, which couple with the intrinsic ones. In addition to the rotation effect, general relativistic effects (gravitational lensing and time delay) will also modulate the individual variation. When a blob is behind the black hole, its apparent size is larger due to lensing, making the blob brighter, and the variation amplitude becomes larger. Such an effect depends strongly on the inclination of the source. All these effects give rise to the apparent variability as recorded by telescopes, which provides information on the physics of the accretion disk, the viewing angle of the source, and the mass of the central black hole.

2. Model and Numerical Results

Before showing the numerical results, we give a brief description of the model. We shall use light curves of orbiting blobs calculated by methods introduced by Bao (1992, see also Bao, Hadrava, and Østgaard 1994). For simplicity, we assume that the photon escapes freely to us once emitted by a blob. This means that the corona around the emitting matter is optically thin. We consider a Schwarzschild black hole to be surrounded by a geometrically thin accretion disk, and neglect the contribution to the energy flux from the higher-order images of the blobs. The blobs are so small that they can be treated as point sources, radiating photons non-isotropically in their rest frame. All blobs are on a relativistic Keplerian disk with an inclination i and with a number density distribution $n(r)$ (numbers per unit ring of the disk), where r is the radial coordinate of the disk. In the numerical simulations, we choose the lifetime of blobs to be radial dependent, and they are $\tau \propto 8r^{1.5}$, i.e., eight times the local Keplerian periods (G, c, M are taken to be unity). Blobs are randomly distributed in their phases, but coherent in their radial distribution.

To achieve a better understanding of the structure of the spectrum of collective blobs, we first show the spectra of a single blob on different orbits with different inclinations. The emitting blobs are assumed to be optically thick, i.e., $a = b = 0$. Fig. 1 exhibits spectra of a blob at orbits of $r = 6.5M$, $20M$, $100M$, with inclinations of $i = 20^\circ$, 60° , 80° and 87° , respectively. The power spectra are characterized by many peaks with each peak corresponding to the orbital frequency (i.e., fundamental frequency f_o) and its harmonics. For a given radius of the orbit, say, $r = 6.5M$, the power contained in the harmonics increases with the inclination. This is because for small inclinations, the light curve of an orbiting blob is close to the sinusoidal one and the variability power resides mostly in the peak at the fundamental frequency. As the inclination increases, gravitational lensing (when the blobs are behind the central hole) starts to deform the sinusoidal signal and produces an extra energy burst with a phase difference of $\pi/2$ from the Doppler boosted one (at $\pi/2$ or at $3\pi/2$

). The deformation is very sensitive to the inclination of the orbit. When the inclination is high, the emitted photons from the blob behind the black hole have trajectories very close to the hole and are lensed. For a given inclination we notice that the lensing effects also depend on the radius of the orbits, which increase with the decrease of the radius. However, they are obviously more sensitive to the inclination. From Fig. 1 it can also be deduced that a pure Newtonian calculation (without considering the lensing effects) should not be applicable when an inclination is larger than 60° . Less pronounced, general relativistic time delay may also contribute to the deformation of the signal.

Given an improved understanding of the behavior of a single blob, it is not difficult to comprehend its collective behavior. Fig. 2 presents spectra for many blobs with inclinations of $i = 20^\circ, 40^\circ, 60^\circ, 80^\circ$. The power is arbitrary and the unit for the frequency is in $\log(f) = -1.5\log(r)$ (again M, G, c are taken to be unity). The number distribution is described by $n(r) \propto r^\delta$ with $\delta = -0.5, 0$, and 0.5 from $r_i = 6.5M$ to $r_o = 54M$. In the simulation, we include a noise, which is chosen as a fraction of the largest signal power. First, the shape of the spectrum is an ideal power-law type in the frequency range corresponding to r_i and r_o . Second, in all the simulations, we find that the spectra slope is most sensitive to the distribution function $n(r)$. That is why we choose $n(r)$ as a basic parameter. Third, we notice that the slope shows no significant variation when the inclination is between 30° and 70° , but when it is higher than 70° , the slopes of the spectra are much flatter. That is because gravitational lensing effect brings more rapid variations into the signal and drives power to the harmonics which becomes comparable to that in the fundamental frequency (see Fig. 1). Finally, the drop-offs at the high frequency end of the spectra, which is the most prominent feature in the power spectra, corresponds to the Keplerian frequency of the innermost orbit of the blobs, i.e., at $-1.5\log(6.5)$ in the Figs. The drop-offs are not clean-cut but smooth, because of the increased amount of power in the harmonics. Their strength is subject to the inclination as well as the noise of the data.

The instabilities probably work most efficiently in the inner disk. The disk is smoother with the increase of radius, which gives a “flattening” frequency at the lower end where there are fewer spots on the disk surface. Theoretically, the inner edge of the disk introduces a drop-off of the variability power at the high frequency end, as beyond that no stable circular orbit exists. The variability is affected by the relativistic rotation of the disk, the brightness of the blobs and their number density within the “flattening” and “drop-off” frequencies, but less strongly outside the frequency range. We therefore expect the variability power spectrum to take different shapes as the two frequencies are crossed. In the simulation of Fig. 3, we choose the blob distribution as in Fig. 3a, where the blobs suddenly reduce in number after r passes a certain border (r_c) of a disk, and it takes the form of $n(r) = r^{-0.3}$ before r_c . The spectrum is a power-law type between Keplerian frequencies of r_c and r_i , and after the

Keplerian frequency at r_c the slope becomes much flatter, leaving a “knee” feature in the spectrum. An observed flattening frequency in the spectrum may shed light on the scale of disk instability or some other turbulent effects occurring on the disk.

3. Discussions

3.1 X-ray variability of AGNs

Variability patterns of AGNs show a great variety, ranging from quasi-periodic flares (e.g., NGC 4051, Lawrence et al. 1985), to flare-like variations (e.g., NGC 6-30-15, Pounds and Turner 1987) and random fluctuations (e.g., NGC 4151, Pounds et al 1986). The variability spectra of most AGNs are characterized by a power-law dependence on the variability frequency i.e. $p(\omega) \sim \omega^{-\beta}$, with a power index ranging from 1 to 2 within frequencies of 10^{-5} – 10^{-3} Hz (Pounds and McHardy 1988). The most typical value of β is about 1.5 (McHardy 1989; Lawrence and Papadakis 1993). Observations suggest that the variability has a self-similar structure and that there is no preferred timescale within the corresponding frequency range.

A power-law spectrum within orbital frequencies is a natural product of collective blobs. If the scenario that clumpy matters orbit a supermassive black hole is true for AGNs or some AGNs, then the self-similar variability pattern will undoubtedly provide valuable information on the AGNs. First, although we are unable to derive any well-defined variability timescales inside the frequency range, yet from the variability power spectrum slope, we may gain insights into some essential properties of the source. It has been shown that the spectra slopes are most sensitive to the distribution of the blobs(see Fig. 2). If the slopes of most of the sources are close to 1.5, then our model predicts that the index of number distribution should be $0 \leq \delta \leq 1$, which, in principle, places a limit on the instability theory of accretion disks or some other theories concerning asymmetric phenomena of a disk. Second, the most remarkable prediction that the model makes is the drop-off frequency in the variability power spectrum resulted from orbiting blobs. It signifies an end of the self-similar structure of the variability (for inclinations less than 80°). The drop-off is a sign of the last orbits of blobs, and is therefore indicative of the mass of the central black hole. It is intrinsic to sources where blobs (flares, vortices, shocks, etc) exist in the innermost parts of accretion disks. In principle, it is identifiable from data, however, general relativistic effects as well as the noise in the observation data may create difficulties. A possibility remains that the Poisson noise of the data is smaller than the signal power at the drop-off and the frequency can be directly singled out. This may hold true for NGC 4051 (Bao & Østgaard, 1994). To identify the “drop-off” frequency in the power spectrum, we need more advanced techniques for data analysis, which may facilitate the recognition of the feature at the high frequency end where

the variance is dominated by the Poisson noise of the data. Meanwhile, observations through a more sensitive detector would help a great deal.

3.2 Variability of stellar black hole candidates

Variability of Galactic black hole candidates show similar behavior to that of AGNs. Rapid X-ray flickering is typical in their X-ray emission, and their power spectra are of a power-law type. But in the frequency range of 0.1 Hz–10 Hz, it is much faster than that of AGNs. This will be clearer when we realize that the corresponding timescales must scale with the mass. The power spectrum slope ranges from 1 to 2, with the average close to 1.5 (Makishima 1988). The similarity suggests that both AGNs and Galactic black hole candidates have a very similar physical mechanism of variability. In addition, a “knee” frequency is identified in the lower end of the power spectrum of the Galactic black hole candidate Cyg X-1 (Nolan et al 1981), and the ‘knee’ point is about 0.1 Hz which corresponds to a timescale much larger than the light travel time associated with a black hole of several solar masses ($< \text{millisecond}$). The low frequency may correspond to some sort of instability scale, which, however, has little implication for the central black hole. Nolan et al (1981) speculated that the ‘knee’ frequency may be related to blobs in the accreting material which are produced by the instabilities of the accretion disk, and that the disk is unstable only inside a certain radius. This could be the case shown in Fig. 3.

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Figure Captions

Figure 1. Variability power spectra of a single blob around a black hole at different radii and inclinations. Units of power are arbitrary and units of frequency are f_0 (orbital frequency). Each column and each row have the same inclination and the same orbital radius as labeled in the figure.

Figure 2. Power spectra of many blobs. Blobs are distributed from $r_i = 6.5M$ to $r_o = 54M$. Units of power are arbitrary and units of frequency are in $-1.5\log(r)$. Each column and each row have the same inclination and the same number distribution $n(r)$ as labeled in the figure.

Figure 3. Power spectra of many blobs. Blobs are distributed from $r_i = 6.5M$ to $r_o = 136M$. The $n(r)$ is plotted as a function of frequency in the upper panel, and the power spectrum is plotted in the lower one. The slope of the spectrum is -1.06. Units of power are arbitrary and units of frequency are $-1.5\log(r)$.

Fig. 1

Fig. 2

Fig. 3