“Echoes” of Black Holes: In Search of Rapidly Spinning Black Holes with Timing Observations

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1. Summary: It has been suggested that the spin of rapidly rotating black holes is the likely source of energy powering extragalactic jets and that it also plays a significant role in the accretion flow dynamics, the shape and luminosity of the disk continuum spectrum, and, in particular, the profile of the observed broad Fe Kα lines. These spectral features specifically have been considered the tell tale sign of rapidly rotating black holes; as such, they have drawn (and will likely do in the future) a lot of the attention and observational resources of several X-ray missions in attempts to deduce, through models of their detailed shapes, the black hole spin, the geometry and the physical processes at play in the black hole accretion flows.

We outline herein the physics behind a novel - not yet detected - type of QuasiPeriodic Oscillation (QPO) associated with accretion flows onto rapidly spinning Black Holes (BH) at frequency $\nu \simeq 1400\,(M/10M_{\odot})^{-1}$ Hz (M being the mass of the accreting BH in solar masses) and indicate that its presence is contingent on the spin parameter a of the accreting black hole being larger than $a \gtrsim 0.9M$. This QPO is based on photon "echoes" rather than fluid oscillations and because of its well defined frequency and properties, its observation would provide unequivocal evidence for a rapidly rotating underlying BH and also a very accurate measure of its mass. This method of black hole spin (and mass) determination, relying exclusively on timing observations, is complementary to that obtained by fitting the profiles of the Fe Kα lines or the accretion disk thermal continuum. Detection of this QPO type would shed light on the processes at work just outside the black hole horizon and would provide a novel perspective for their study. We indicate that observations of sensitivity higher than hitherto achieved by existing instrumentation will be able to detect or confirm the absence of these QPOs.

2. General Background: Following the realization that Galactic Black Hole Candidates (GBHC; X-ray binary sources whose compact object is estimated to have a mass in excess of $\sim 4\,M_{\odot}$) and the centers of Active Galactic Nuclei (AGN) harbor Black Holes, a great effort has been expended in the determination of their masses, spin and accretion flow physics; in fact, *the details of the conversion of accretion kinetic energy onto black holes into radiation remains an open question and a major quest of present day astrophysics.* Progress has been slow, hampered the small size of these systems, well beyond the resolving power of our present telescopes. As such, progress in this direction has been made indirectly through modeling and interpretation of spectroscopic and timing observations. However, standing in the way of such an approach is the fact that, despite their unresolved size, accretion flows onto black holes span several decades in radius; this is the likely reason that the corresponding Energy Spectra and variability Power Spectra (PSD) span also a large number of decades in energy and Fourier frequency with roughly constant power per decade (see e.g [1, 2]).

These broad distributions of the energy and power spectra of accreting black holes compound the difficulties of determining the physical conditions (density, temperature, ionization state) of the accreting plasma as a function of radius, necessary for comparison with the theoretical models. Nonetheless, at least **in the spectral domain**, there are several broad, ubiquitous features which have been identified with components of the accretion flows: 1. A broad, quasi-thermal feature in the Optical-UV in AGN and in soft ($E \lesssim 1$ keV) X-rays in GBHC, referred to as the Big Blue Bump (BBB) or as the Multi-Color Disk (MCD) respectively; this is attributed to emission by a geometrically thin, optically thick accretion disk that presumably extends to r_{ISCO}, the radius of the Innermost Stable Circular Orbit (ISCO) of massive particles in orbit around the black hole. 2. A harder ($E \gtrsim 2$ keV) X-ray component, attributed to emission by a hot corona ($T \sim 10^8 - 10^9$ K) overlying the thin disk; this up-Comptonizes the disk softer photons to produce the hard ($E \sim 2 - 50$ keV) X-ray emission present both in AGN and GBHC. 3. Broad Infrared (1 - 100 micron) emission with luminosity comparable to that of the O-UV, attributed to a geometrically thick, cool, neutral "torus" at distances much larger than the black hole radius ($\sim 10^4 - 10^6\, R_S$), which apparently reprocesses the O-UV and X-ray photons to produce the observed AGN Infrared emission (this feature is absent in GBHC). **In the time domain**, the broad band variability power spectra of accreting black holes are less well understood, with no particular features identifiable as such with specific components of the accretion flow.

2.1 Spectral Lines and QPOs: Much finer probes of black hole accretion flows are spectral and timing **narrow band features**, namely **atomic transitions** and **Quasi-Periodic Oscillations (QPO)**. These feature prominently in the spectra of GBHC and AGN and the power spectra of accreting neutron stars [3], Galactic Black Holes Candidates [4] and have recently been discovered also in AGN [5].

Spectral lines have been instrumental in providing estimates of the masses of accreting black holes. In the case of GBHC this was achieved through the determination of the X-ray binary orbit elements [4], while in the case of AGN through the line reverberation technique [6], in a synergistic combination of spectral and temporal observations. These demonstrated the indispensable role of timing observations: They provide the means for inverting the column density information obtained by optically thin spectra into density and size separately, needed to determine the dynamics of the system. Furthermore, profiles of lines yield information about the velocity field emitting plasma: The nearly symmetric O-UV lines in AGN imply isotropic velocity distribution of the emitting gas; "double horned" lines signify emission from a disk, while broad, blue-shifted absorption troughs are the hallmarks of winds. By contrast, the discovery and rich phenomenology of QPO, has been less fertile in providing as definitive information about the accretion flow kinematics as the spectral lines, but their wide range of frequencies, reaching the kHz in neutron stars, is evidence for interesting dynamical processes at the deepest regions of their gravitational potential.

2.2 Black Hole Spin: Fe Kα Line vs. MCD Spectrum: The Newtonian-like character of GBHC and AGN potentials naturally puts emphasis on processes taking place at the smallest radii, the region where most energy is released. However, near the BH horizon, the deviations from Newtonian gravity are significant and the precise geometry of space influences the dynamics of accretion, its efficiency and the spectra emitted in that region. At the same time, because this is the region of highest velocities and highest ionization of the accreting plasma, its probes are expected to involve the broadest and highest ionization atomic transitions, varying on the shortest time scales (highest Fourier frequencies).

Consistent with these considerations, the broadest line feature detected so far is that of the Fe Kα line, produced either by fluorescence on cold matter at $E = 6.4$ keV or by photoionization of H-like or He-like Fe at 6.9 keV and 6.7 keV respectively. The prevailing view at the time of writing is that this feature is emitted on the surface of the "cool", geometrically thin, optically thick, Keplerian accretion disk (the source of the BBB and

MCD features), from the reprocessing of the coronal X-rays. This specific arrangement and the accurately known kinematics of Keplerian black hole disks allow for the precise modeling of the Fe line profiles. Most important for these models is that the disks terminate at an inner radius $r_{\rm in}$ equal to r_{ISCO}. Then, the value of the Keplerian velocity at ISCO along with the disk inclination determine the width of the corresponding Fe Kα line profile from the combined effects of the Doppler and gravitational redshifts of the line emitting plasma near r_{ISCO} [7].

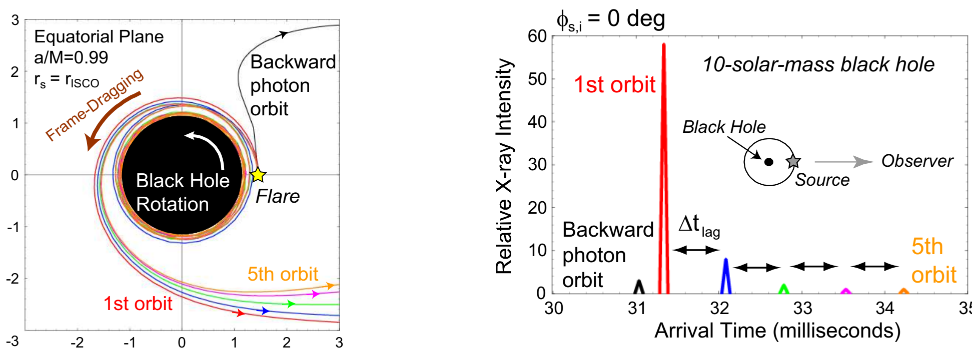

Figure 1: (a) Sample photon orbits for isotropic emission from a source in Keplerian orbit at the ISCO of a BH of $M = 10M_\odot$ and $a = 0.99$. (b) The arrival times and number of photons in trajectories close to those of shown in (a) collected at $r = 600M$ between phases 0°-1°, i.e the response function for $\phi = 0°$.

The increase in sensitivity and spectral resolution of X-ray missions from 1990s on allowed fits to the Fe Kα line profiles that showed them to be too broad for the kinematics of Keplerian disks around Schwarzschild black holes. Because r_{ISCO} approaches the Kerr black hole horizon and the Keplerian speed at r_{ISCO} approaches c as the BH spin a increases to $a \to M$, the width of the Fe Kα line increases correspondingly [8, 9] to values consistent with observation. Matching model line profiles to observation can and has been used to determine the value of the black hole spin a and the disk inclination. Fits of the Fe Kα line profile of the Seyfert 1 MCG 6–30–15 [10, 11] have thus indicated for the specific object a value $a \simeq 0.99M$.

More recently values of the BH spin a were derived employing models of the continuum spectra of the MCD[12] of GBHC that incorporate all the effects of photon transfer in the Kerr geometry. The method has been applied to the data of the GBHC GRS 1915+105 [13] and GRO J1655-40 [14] to obtain values in the range $a = 0.98$-1 and $a = 0.65$-75 respectively. Interestingly, this spin value of GRO J1655-40 is in disagreement with that obtained by modeling the Fe Kα line [15] ($a \simeq 1$ with some caveats), while disagreement in the disk parameters was also found in spectral fits of SWIFT J1753.9-1027[15, 16] indicating tension in the spectral determination of a. One should note that there is also tension between the spectral and variability observations of the Fe Kα line, at least in the case of AGN, which it is found to be less variable than the continuum[17, 18], contrary to expectation.

While these results suggest strongly the presence of rapidly spinning BH in certain objects, definitive conclusions rest on a number of caveats: The X-ray illumination of the disk has to be highly concentrated near its inner edge (the fits of [20] require an illumination profile

$I_X \propto r^{-5}$, much steeper than that of standard accretion disks, prompting the authors to suggest additional energy input near $r_{\rm in}$ from the BH spin by magnetic fields). The Fe Kα emission is sensitive to the ionization state of the plasma (highly ionized plasma would produce little Fe Kα line [19]). Similarly, estimates from fits to the MCD spectra depend on the poorly known spectral hardening factor the disk inclination and the possibility of energy input near r_{ISCO} by the black hole spin[21].

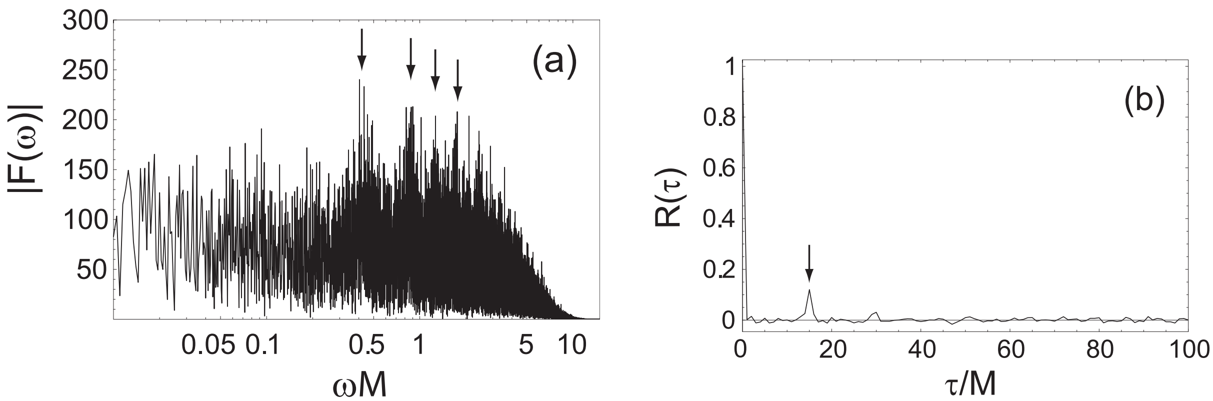

Figure 2: The power spectrum (a) and the Autocorrelation function (b) of the model light curve shown in Fig. 3(a), in dimensionless units in ω and τ without the constant flux component or Poisson noise. The harmonically spaced QPO and the secondary peak are apparent, despite the randomness of the signal.

3. Photon "Echoes" in Kerr Geometry: A common feature emerging from the models of the broad Fe Kα lines and recent theoretical developments[21] is the increased X-ray input at the innermost disk radii around rapidly spinning black holes. This is likely to be in the form of flares mediated by the shearing and annihilation of magnetic fields at the location. The time scale of magnetic field annihilation is generally short compared to other time scales, most notably the Keplerian period, and the corresponding flares could be thought of a series of short bursts of photons. However, because of the large space curvature at their emission region, these photons reach distant observers through different paths to produce "echoes" of the original photon release. The delay times between these "echo" bursts depend on the relative phase between the source (in orbit around the black hole) and the observer. Thus, for a source at phase $\phi \simeq 180°$ in a Schwarzschild black hole, photons at paths across the hole arrive with lag $\Delta t \simeq 0$ by symmetry; however for a source at phase $0°$, while most photons arrive at the observer directly, several photons will reach him/her after a full orbit around the black hole at the circular photon orbit, $r_{\rm ph} = 3M$, to arrive with a lag $\Delta t \simeq 2\pi r_{\rm ph}/(1-2M/r_{\rm ph})^{1/2} \simeq 32M$. It has been noted though that the fraction of these photons is very small ($\lesssim 1\%$) to be of significance. For random source phases, the corresponding lags range between 0 and $32M$, and in the absence of a specific phase that might be favored for flare production, they average to zero[22].

However, this situation changes drastically[22] for flares that take place *inside* the ergosphere of a Kerr black hole, i.e. at $r < 2M$ in its equator (for disks in equatorial Kerr orbits r_{ISCO} lies inside the ergosphere, $r_{ISCO} < 2M$, for black hole spin $a \gtrsim 0.94\,M$): In this case, frame dragging along with the increased Lorentz boost due to the higher Keplerian disk velocity, thrusts all photons in the direction of black hole rotation. To reach an observer,

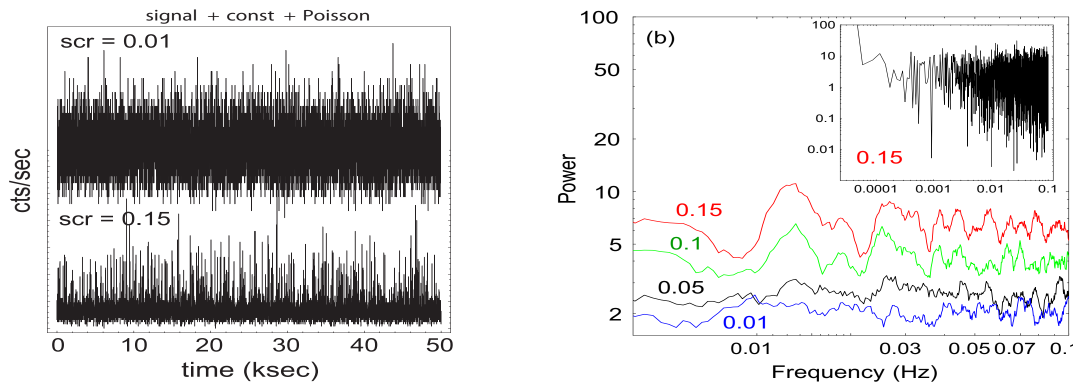

Figure 3: (a) Model light curve computed as discussed in the text for BH mass $M_{\rm BH} = 10^6 M_\odot$, signal-to-constant flux ratios $SCR = 0.15, 0.01$ averaged over 5 sec to produce a mean flux consistent with observations. (b) The corresponding PSD. Inset, the raw PSD. The colored curves are the Leahy normalized PSD for the values of SCR shown in the figure. These PSD are obtained from the raw one by rebinning and averaging over several frequency bins. The QPOs are discernible at the proper frequency for SCR as low as 0.05.

almost all photons of an isotropic (in the fluid frame) flare event have to travel around the black hole, *independent of the observer's relative phase with the source* (see Fig. 1). This increases significantly the probability that photons reach the observer after one (or more) additional orbits around the black hole (roughly 15% reach the observer after one additional full orbit and 2%-3% after 2 or more). Most importantly, the separation in time of the photons in these different paths, equal to the photon travel time at its circular orbit as perceived at infinity, $\Delta t \simeq 14\,M$, is now constant, i.e. source phase independent[22] (it should be noted that this property is preserved for 3-dimensional photon orbits[23]) . Therefore, a flaring event near r_{ISCO} with $r_{ISCO} < 2M$, will be perceived as a series of flares, i.e. "echoes", of decreasing amplitude, separated by the constant lag of $\Delta t \simeq 14\,M$.

3.1 Response Function and Model Light Curves: The time variability of a flaring accretion disk can be modeled by first computing its response function, namely the time development perceived by faraway observers to an impulsive photon injection near r_{ISCO} for all relative phases between source and observer. An example is shown in Fig. 1b for a BH of $M = 10M_\odot$, $a = 0.99M$, and source phase $\phi = 0°$, i.e. for the orbits shown in Fig. 1a. This is produced by computing a large number of photon orbits, emitted isotropically in the fluid frame and collecting them as a function of time at $r = 600M$ and phase $\phi = 0°$. A small number of backward emitted photons (Fib. 1a) are the first to arrive, followed by a major burst at $t = 627M = 31.4$ msec, a burst $6\times$ smaller at $t = 641M = 32.1$ msec and a yet smaller at $t = 655M = 32.8$ msec. The response for different values of the phase ϕ has a similar form i.e. a number of individual short peaks of different arrival times but with *the same constant separation of 14M*[22]. The constant value of the interpeak interval is most important: It guarantees that the AutoCorrelation Function (ACF) of any light curve, besides the peak at lag $\tau = 0$, it will exhibit a second peak at $\tau = 14M$. Since the variability Power Spectrum of a signal is the Fourier Transform of its ACF, *the lag in the time domain will manifest itself in the frequency domain as a QPO at a frequency* $\nu = 1/14M \simeq 1400(10M_\odot/M)$ *Hz!*

Model light curves have been produced[22] by convolving the Response Function with a flare prescription near r_{ISCO}. The flares were set at random values of the phase ϕ with Poisson distribution in time of mean value equal to the Keplerian period to avoid introducing any periodicities in the signal. An example of such a model light curve in shown in Fig. 3a appropriate for an AGN of black hole mass $M = 10^6 M_\odot$ and $a = 0.99M$, including a constant flux component to simulate emission from radii $r > 2M$ of the disk. While apparently random, the constant-lag information is present the signal and manifests in the Power Spectrum and ACF shown in Figs. 2a and 2b respectively. The peak at $\tau = 14M$ in the ACF and the harmonically spaced QPOs in the PSD are plainly apparent.

3.3 "Echo"–QPO Properties and Observability: The specific QPO discussed above, is different from those more commonly discussed in the literature in several respects: 1. It is predicted than postdicted. 2. Its nature is well understood. 3. It involves no apparent periodicity or oscillatory behavior in the source light curve. 4. Because it is of geometric origin its frequency is independent of the source flux, contrary to most QPOs whose frequencies increase with increasing source flux[3].

Some of the above properties are not novel but are found in the QPO of certain GBHC: For example there have been observations of harmonically spaced QPO peaks in the light curve of X-ray nova XTE 1550-564 [25], and also QPOs in GRO J1655-40 whose frequencies at $\nu = 300$ and 450 Hz do not depend on the source flux [24]. However, none of these were at the predicted frequency and analyses to date in the literature were done in Fourier space and cannot preclude an echo-type ACF (We actually have computed the ACF of XTE 1550-564 and ascertained, that its harmonically spaced QPOs are not due to "echoes").

Concerning the observability of the "Echo"-QPO, estimates can be made based e.g. on the QPO of GRO J1655-40[24] at $\nu \simeq 450$ Hz, close to the predicted frequency $\nu \simeq 1400(10M_\odot/M)$ Hz discussed above: The 450 Hz QPO shows up above the RXTE Poisson noise, but presumably "sits" on top of the steeply decreasing PSD of GRO J1655-40. Assuming that the "Echo"–QPO sits on the same decreasing continuum PSD but at tenfold higher frequency, even with $\nu/\Delta\nu \sim 10$ as the 450 Hz QPO, it is doubtful that it would be discernible above the Poisson noise of the same level. Assuming it is present, its detection requires a mission that can deliver a reduction in the Poisson noise level by a factor of $\gtrsim 10$ over RXTE for a source of a similar flux.

A more detailed simulation, appropriate for a 300 ksec observation of an AGN of $M = 10^6 M_\odot$ and $a = 0.99M$ is given in Fig. 3. This assumes a source of 2 counts/sec which in addition to the flaring contribution from within the ergosphere includes also emission from the rest of the disk. As noted above, emission outside the ergosphere yields variable lags and hence dilutes the QPO signal. We parameterize the contribution of the outer disk in terms of the ratio of the mean flux rates of the two components by the 'Signal-to-constant flux ratio' SCR. The two light curves of Fig. 3a correspond to the same count rate but to the SCR values noted in the figure, averaged over 5 seconds and including Poisson noise. Fig. 3b shows the Leahy normalized Power Spectra of the light curves of Fig. 3a. The inset shows the raw spectrum while the rest of the figure frequency averages for the noted values of SCR, indicating that the QPO is indeed observable in a 300 ksec observation for SCR values greater than 0.05.

The presence of an ergosphere and the need of increased activity in its vicinity implied by spectral interpretations of the Fe Kα line and the MCD spectra implies the presence of the

Echo–QPO discussed. These may be already present in the AGN data and their presence should be able to be confirmed or refuted with a tenfold improvement in X-ray sensitivity; absence of their detection will set limits on the variations of the processes taking place within the BH ergosphere and will induce a revision of the current interpretation and the processes at work in the formation of the Fe Kα line.

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