A Review of Disk-Corona Oscillations

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Abstract. Low frequency $(\approx 0.1 - 35 \text{ Hz})$ quasi-periodic oscillations of the X-ray flux characterize many of the black hole candidates, in particular those which have radio evidence for jets. These QPO have amplitudes of up to 20 % in the states of black hole novae which are called very high and intermediate and are correlated with the break frequency of the band-limited low frequency white noise. With transition to the state called the soft high state, both the QPO and the noise disappear. While the noise is strong in the low hard states like that of Cyg X-1, the QPO, when present, are weak and broad. In their strong manifestations, these QPO have the curious property of appearing to have the spectrum of the power-law component which dominates in the low state, while correlations between their frequency and the disk component in the spectrum imply control by the disk. The correlations, the harmonic structure of the QPO, and the phase lags have complex behavior in the same source (GRS 1915+105, XTE J1550-564). The phenomena point to interaction between the disk and the corona, for which there are several interesting ideas.

Keywords: quasi-periodic oscillations, microquasars, black hole candidates

1. Introduction

Disk-corona oscillations, as discussed in this paper, refer to the oscillations in X-ray flux, appearing as quasi-periodic oscillations (QPO) in the power density spectra, which are in the non-thermal spectra possibly originating in a corona, but which appear to be related to optically-thick emission associated with the accretion disk. The QPO can have an amplitude of 10–20 %. In the power density spectra of black hole candidates (BHCs), a subset of which are known to b e microquasars, several low frequency features have appeared. For a given source several QPOs can appear simultaneously, in which case it is clear that there are more than one phenomenon manifested. The characteristics of the features seen in the range 1–15 Hz are best known, but they have been seen below 1 Hz and above 15 Hz.

These oscillations were seen with Ginga in GX 339–4 (Miyamoto et al. 1991) and Nova Muscae (Takizawa et al. 1997). The frequencies increased with the source intensity, not always in the same way. When RXTE discovered GRS 1915+105 to be active in 1996, the oscillations were soon found to be prominent during long episodes of hard flux and relative quiescence, and the oscillation frequencies were found to be strongly correlated with the source intensity (Chen et al. 1997).

GRO J1655–40 became active and showed the same kind of features (Remillard et al. 1999). By the end of 1999, RXTE had observed recurrences of the black hole candidate transient 4U 1630–47, and 4 new transients, all of which exhibited at some stages very high amplitude low frequency QPOs: GRS 1739–278, XTE J1748–288, XTE J1550–564, and XTE J1859+226.

Cyg X–1, 1E 1740.7–2942, GRS 1758–258, and several transient sources which did not get very bright, have been known for band limited white noise. Sometimes there have been peaks and even a harmonic in the frequency range where the spectra roll over (Cui et al. 1997; Smith et al. 1997). These have lower amplitudes, 5 %, and sometimes are hard to distinguish from a sharp transition in the power density spectrum. In Cyg X–1 the amplitude was highest during the transitions between low and high states, appropriately called the "intermediate state".

2. Characteristics of the QPO

Usually the QPO feature has at least one harmonic. Sometimes a peak at what would be the subharmonic is present. For simplicity we refer to the dominant peak as representing the phenomenon, whatever may be the real fundamental of the oscillation.

Almost always it is present over a range of luminosities and the frequency varies with luminosity. In most cases the frequency has increased with count rate and indeed with luminosity, when the spectrum has been taken into account. GRO J1655–40 was a notable exception, with the frequency generally decreasing with the total luminosity. However, Sobczak et al. (2000) found that frequency was positively correlated with the flux of the soft spectral component. There may be some counter-examples. In 4U 1630–47, a square wave oscillation of flux at a lower frequency was observed (Dieters et al. 2000) and two low frequency QPOs were observed in the 1-10 Hz range, one moving with the flux, the other stationary. These frequencies are at least a factor of 10 too low to be related to the inner most stable orbit of the accretion disk, for which the Kepler frequency would be 2200 Hz $(M/M_{\odot})^{-1}$.

The energy spectra of the sources can usually be well or almost described by an optically thick component and a non-thermal component. A physical model would be a disk spectrum Comptonized in a hot corona, but it can be approximated by the a multicolored disk and a power-law. The QPO usually appears when the flux is dominated by a relatively hard power-law-like component.

The energy spectrum of the QPO fundamental is that of the powerlaw component. Cui et al. (1999) plot (for XTE J1550–564) the root mean square (rms) amplitude of the QPO fundamental and harmonic with energy. The fundamental tracks the energy spectrum. Curiously the harmonic reverses and declines with energy, in comparison.

It was shown (Wijnands & van der Klis 1999b) that for a number of observations of BHCs, the break frequency of the band limited white noise component was about a fifth of the QPO frequency. However Morgan et al. (1997) exhibit power density spectra with the QPO frequency clearly corresponding to the break frequency. The exact connection between the two requires further study.

For GRS 1915+105 there is a great deal of data from different states and correlations between characteristics have been studied with several approaches. Markwardt et al. (1999) looked at many observations in which on time scales of minutes, the flux varied strongly (factors of 2- 10). They averaged power spectra for given flux levels and found that the average exhibited a strong correlation of frequency of the QPO with the bolometric flux of the disk component in a spectral fit (4 s spectra), above the frequency of about 4 Hz. Muno et al. (1999) computed spectral parameters and power spectra for 16 s intervals of a larger set of observations, including those in which variations were slow. Frequency appears correlated with disk inner temperature for many of these. Plots with respect to disk black body flux, temperature, and inner radius all show runs of correlated data points, but also subsets clearly violating the correlation or having a very different correlation, indicating the behavior is not unique.

It is tempting to think of the frequency as related to the Kepler frequency at some radius, although the factor and physical origin of the relation may not be clear. Trudolyubov et al. (2000) leapfrog from the dependences of f_K and the viscous time scale at the radius to the relation between the duration of the hard state and the minimum frequency observed. The duration and frequency are easy to measure. The inner radius of the disk is difficult to measure, especially when the disk inner temperature appears to be low and the radius large, so that the RXTE PCA can only "see" the Wien tail of the energy spectrum. This gives $t \propto f_K^{-7/3}$ with a proportionality depending on the rate of mass flow through the shell. For the sets of observations with hard dips, this correlation appears to be a good fit. For the observations with soft dips, the dependence is significantly steeper.

For a given mass accretion rate in the disk, the temperature has a constrained relation to the radius, of course. Belloni et al. (2000) examined whether this relation holds and allows identification of the mass flow in the disk. Their aim was to compare to the mass loss rate in the radio emitting plasma that is ejected. These questions are just the sort that can give physical insight into the correct description of

the disk accretion and the generation of winds and jets, but the X-ray calibration to date limits the conclusions.

The confusion of opposite dependence between frequency and total count rate in GRO J1655–40 and GRS 1915+105 appeared clarified by their having similar correlation with the disk flux alone. Furthermore, Sobczak et al. (2000) found that for XTE J1550–564, while the dependence of the QPO frequency with either temperature or radius was complex, the frequency did increase with disk flux. But from the point of view of the Accretion Ejection Instability (Tagger & Pellat 1999; Rodriguez et al. 2000) the complex dependence of the QPO frequency on radius is just what would be expected if the inner disk of GRO J1655–40 is nearer to the black hole, where relativistic effects can cause a turnover of the curve.

To interpret these correlations, physical models are needed for which the data can determine the parameters reliably. In deducing radii of the disk, even with the caveat that it is the optically thick disk, we are using zero-order approximations, when we know that we should consider the scattering atmosphere of the disk together with advective and wind flows (Merloni et al. 2000). However, although the meaning of the slopes may need modification, the fits to the data show that correlated changes occur, with values of the parameters often in realistic ranges.

3. Relation of Disk-Corona Oscillations to other QPO

Although much of the discussion has been in terms of the inner radius of an optically thick accretion disk that is being seen in the X-ray spectrum, it should be remembered that the QPO has appeared to occur simultaneously with the QPO that appears at much higher frequencies. It has seemed reasonable that the latter could reflect either the Kepler orbital frequency near the Innermost Stable Circular Orbit about black holes or the eigenfrequency of the fundamental modes of oscillation of the inner disk. High frequencies have been reported for 5 BHCs. For GRO J1655–40, XTE J1550–564, and XTE J1859+226, they have occurred together. Obviously if the higher frequency reflects emission from near the inner edge of the disk, the lower frequency cannot be the same thing, although it could be a different time scale at the same place. Alternatively, the inner disk may not be otherwise seen directly, while the lower frequency could reflect a transition region in the disk rather than the inner radius.

For GX 339–4 and GRS 1739–278 the low frequencies were only seen around 6 Hz and 5 Hz respectively. For Nova Muscae, GRS 1915+105, XTE J1550–564, 4U 1630–472, XTE J1859-277, values sampled include similar ranges within 0.08-18 Hz, while the high frequencies of the last 4 of these were 67 Hz, 161-237 Hz, 185 Hz, and 150-200 Hz. For two of the sources, GRO J1655–40 and XTE J1748–288, the low frequencies were higher, 14-35 Hz. GRO J1655–40's high frequency was also higher, 300-400 Hz. Dynamical masses are so far known only for GRO J1655– 40 and Nova Muscae. How the frequencies scale with black hole mass is not yet clear.

QPOs at frequencies an order of magnitude below these disk-corona oscillations also occur. One type of variation which generates very low frequency oscillations in the power spectra are square-wave modulations of the flux originally called "flip-flops" by Miyamoto et al. (1991), and also dips. GRS 1915+105 has a 15 mHz feature whose folded light curve looks almost like an occultation (Morgan et al. 1997).

The disk-corona oscillation is in a frequency range just below the Horizontal Branch Oscillations (HBO) of Low Mass Binary Neutron Stars and they can look similar in harmonic structure. Usually the amplitude is lower. The HBO and Normal Branch frequencies of the Atoll and Z sources have been found to be correlated to the lower of two kilohertz frequencies. For the BHCs, Psaltis et al. (1999) see features, sometimes very broad, that they consider to be counterparts of the neutron star lower kilohertz frequency. They find the disk-corona oscillation and this oscillation to be related in the same way as are the HBO and the lower kilohertz oscillation. The ratio of the average lower frequency in the BHCs and of the HBO in the neutron star sources could be consistent with being inversely proportional to the mass of the compact object (Chen et al. 1997).

4. Relation to Black Hole Accretion States

Most black hole candidate transients have outbursts which last several months, but not as long as has GRS 1915+105. They usually have a well defined onset, rise, peak, and decay, although there are rather frequently one or more brightenings during the decay. GRS 1915+105 has for several years now evolved from one recurrence to another. GRO J1655–40 and XTE J1550–560 recurred after a year, but they had clearly gone into quiescence first. In a typical case there is a rising phase, frequently a very high state (VHS), a high soft state (HS) and decay through an intermediate state (IS) to a low hard state (LS) and finally a quiescent state.

RXTE has had a number of successful observations of rising phases (XTE J1550–564, Cui et al. 1999; 4U 1630–472, Dieters et al. 2000; XTE J1859+226, Markwardt et al. 1999) In these cases the spectra

started out harder than achieved subsequently in the outburst. The spectrum softens as the flux rises. The disk-corona oscillation starts below 1 Hz with high amplitude and rises in frequency, increasing in width and decreasing in amplitude somewhat. But the time scale for these changes is days rather than the minutes required for the GRS 1915+105 hard dip recoveries.

At the end of the rising phase, the transient may be in the VHS with a strong power law and a strong disk flux. In both the VHS and IS the QPO is present. In the HS the soft component is very bright (several tenths of the Eddington limit). A relatively steep power-law component extending to high energy may be of a completely different origin than the Compton up scattering in a hot corona that is favored for explaining the VHS. There are NO QPOs in the HS.

In the case of GRS1915+105, we discuss a scenario of mass flow in the disk, removal of the disk into a corona and ejection into jets. Does this scenario apply to the transient outbursts? In the VHS there is outflow, because the radio emission often starts sometime during the rising phase. The mass accretion rate in the outer disk is large and the inner radius of the disk is large. As the mass flow rate subsides the disk collapses to be optically thick, or at least it is optically thick farther in toward the center. At a lower rate, there are also radio injections associated with the transitions to the HS and out of it to the IS (e.g. Hjellming et al. 2000) from comparison of the radio and X-ray transitions (for XTE J1748–288 and XTE J1859+226). This scenario would imply that spectral fits obtain larger inner radii for the disk in the VHS than in the HS, but only a factor of 2 seems to have been observed. Much needs to be done to understand the evolution.

5. Explanations for the Low Frequency QPO

The flux that is oscillating appears to be the hard power-law component of the spectrum, the candidate for indicating the presence of a hot corona. The thermal photons from the disk would be the dominant source of the seed photons to be up-scattered in the corona. Whether the corona is spherical and central or extended over the inner disk, or whether there is simultaneously spherical infall is not clear. Radio observations are indicating (See Fender, this volume) outflow and synchrotron radiation. A number of models have been suggested and would explain some of the observations. I only mention some of the ideas.

Disk-corona oscillations are probably not like the possible coronal radial infall oscillations suggested for the normal branch oscillations

at about 6 Hz in the neutron star Z sources. Neither observations or simulations show the large amplitude and variability.

It has been suggested that the HBO in neutron stars are due to the Lense-Thirring frame dragging in the strong gravitational field close to rather heavy neutron stars (twice the nodal precession frquency of slightly tilted and elliptical orbits.) Systematic similarity of the neutron stars and BHCs has been claimed, as mentioned above. In some cases the approximately linear relation between two frequencies in the BHCs and the HBO and lower kilohertz frequencies for the neutron stars is impressive. Psaltis & Norman (2000) have made a case that the frequencies observed are the resonant frequencies in the disk, whatever the mechanism for modulating the X-ray flux.

One idea that appears to generate the right order of magnitude of frequencies and similar dependences to those observed is that of shocks at the inner disk and oscillation of the shock position (Molteni et al. 1996; Manickam & Chakrabarti 1999), but there have been objections that such shocks cannot be generated. The correlations between duration of the dips in GRS 1915+105 with the frequency of the QPO are difficult to distinguish from the correlations expected in a viscous refilling model (Trudolyubov et al. 2000).

Finally, Tagger & Pellat (1999) make a case that Rossby waves of the Accretion Injection Instability are a natural way to carry gas and energy from a disk to the corona and thence into a wind or jet and to generate oscillations in the flux.

The data available so far has enough detail to provide many guideposts and constraints to the theories. These low frequency disk-corona oscillations are very common in BHCs and are a challenging physics problem which involves important aspects of accretion onto black holes.

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