Inner Disk Oscillations and QPOs in Relativistic Jet Sources

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Abstract. Recent results on the inner disk oscillations found in GRS 1915+105 are reviewed. QPOs during the low state are used as a marker for such oscillations and the physical picture emerging from a combined X-ray spectral and timing analysis is examined. The relationship between inner disk oscillations and synchrotron radio emission is critically evaluated.

Keywords: Accretion, accretion disks – X-rays: stars: individual (GRS 1915+105)

1. Introduction

One of the remarkable features of the X-ray variability of the Galactic relativistic jet source GRS 1915+105 is the rapid intensity variations associated with repeatable and distinct spectral characteristics. Belloni et al. (1997) found that the source shows distinct and different inner disk radius during the “quiescence” and outburst which can be interpreted as the vanishing of the bright inner disk during the quiescence. Detection of rapid radio oscillations near the onset of superluminally moving ejecta prompted Fender et al. (1999) to suggest that such X-ray inner disk oscillations could be the underlying reason for the ejection of the synchrotron cloud responsible for the radio emission.

Ever since its discovery (Castro-Tirado et al. 1992) GRS 1915+105 has been exhibiting a rich variety of X-ray variability characteristics. Greiner et al. (1996) presented the RXTE observations of the source which included repeated patterns of brightness sputters, large amplitude oscillations, fast oscillations and several incidences of prolonged lulls. Belloni et al. (1997) classified some of the oscillatory X-ray variations as “outbursts” and from a time resolved spectral analysis found evidence for the disappearance of the inner disk during these oscillations. They also discovered a strong correlation between the quiescent phase and burst duration. Taam, Chen, and Swank (1997) detected a wide range of transient activity including regular bursts with a recurrence time of about one minute and irregular bursts. Paul et al. (1998) detected several types of such bursts using the IXAE data and found evidence for matter disappearing into the event horizon of the black
Yadav et al. (1999) made a systematic analysis of these bursts and classified them based on the recurrence time.

Belloni et al. (2000a) made a detailed evaluation of the X-ray variability characteristics of GRS 1915+105 and classified the variations in 12 different classes. To understand the basic nature of these classes, in Figure 1 we give the representative light curves and hardness ratios obtained from the RXTE archives. The total count rate, R, is in the units of $10^4$ counts s$^{-1}$ and it is vertically shifted by 5 units. The hardness ratio H1 (5 – 13 keV to 2 – 5 keV ratio) is scaled by 5 and shifted by 2 units and the hardness ratio H2 (> 13 keV to 2 – 13 keV ratio) is scaled up by 10 and shifted by 4 units. The hardness ratio H1 is a measure of the disk blackbody temperature and H2 is a measure of the intensity of the hard power-law, presumably arising from a thermal-Compton cloud.

The X-ray variability classes which show steady behavior during one orbit of RXTE are shown in the top panel of the figure. Class $\phi$ is characterized by low count rate, low H1 and very low H2. It is also devoid of any strong variability. Class $\chi$ is characterized by strong 0.5 – 10 Hz QPO and it resembles the intermediate state of other black hole sources (Trudolyubov et al. 1999b). Classes $\delta$, $\gamma$ and $\mu$ are high-soft states of the source and occasionally the 67 Hz QPOs are seen in these states (Morgan et al. 1997).

The various X-ray variability classes which exhibit inner disk oscillations are shown in the middle panel of Figure 1. The distinguishing feature is the sharp (< 10 s) change in the intensity state. During the high state of these oscillations the source exhibits all the temporal and spectral characteristics of the high-soft state of the source and during the low state it exhibits all characteristics of the low-hard state of the source (Rao et al. 2000b). The drastic change in H2, signifying a change in the Compton cloud, is a common feature of this class. The behavior can be regular (class $\rho$) and it can remain in this class for periods up to several tens of days. In class $\alpha$ the source reverts back and forth between class $\chi$ and class $\rho$. During the quiescent periods of all these classes the 0.5 – 10 Hz QPO is always present.

In contrast to such inner disk oscillations, classes $\nu$, $\theta$, and $\beta$ show a more gradual change from a high-soft to low-hard state and they are characterized by a sharp soft dip when both H1 and H2 are low and the variability too drops to a low level. Radio oscillations are associated with these classes (Eikenberry et al. 1998; Mirabel et al. 1998).
2. Inner Disk Oscillations and QPOs

One of the remarkable features of the inner disk oscillations is the presence of the ubiquitous 0.5 – 10 Hz QPO during the quiescent state of the oscillations. This type of QPO is found during the low-hard state of the source (and also in the low-hard state of other jet sources as well), and it is used as a marker for the low-hard state of the source (Muno et al. 1999; Trudolyubov et al. 1999b).

Reig et al. (2000) made a detailed study of the QPO phenomena in the $\chi_1$ and $\chi_3$ classes and found a correlation between the QPO frequency and the observed phase lag in the Fourier cross-spectrum in two energy channels. Nobili et al. (2000) have interpreted this correla-
tion as due to arising from the geometry of the region producing the Compton spectrum, assumed to be arising from a corona formed by the puffed up inner regions of the accretion disk. Rao et al. (2000a) made a detailed spectral study during the $\chi^3$ state of the source and identified three spectral components. They found that the QPOs are due to the Compton component and they invoked an accretion disk shock to explain the QPO phenomena.

The large rms amplitude (about 10%), narrow width and the relative stability over considerably long durations makes it difficult to explain the 0.5 – 10 Hz QPO on the basis of any disk oscillation model. Chakrabarti & Manickam (2000) interpreted the QPOs as due to the oscillation of the region responsible for the hard radiation, i.e., the post-shock region. They also detected a correlation between the average frequency of the QPO and the duration of the ‘off’ states. A similar correlation with centroid frequencies were also found by Trudolyubov, Churazov, & Gilfanov (1999a).

There have been attempts to explain the rapid variability seen in GRS 1915+105 using disk instability models. Belloni et al. (1997) have tried to explain the repeated patterns as due to the appearance and disappearance of the inner accretion disk. Nayakshin et al. (1999) have investigated the different accretion models and viscosity prescriptions and attempted to explain the temporal behavior of GRS 1915+105. In particular, they have shown that the accretion instability in a slim disk is not likely to adequately account for the behavior of GRS 1915+105 (because of the difficulty in maintaining the high state for long) and the appearance of the inner accretion disk, as postulated by Belloni et al. (1997), will take a time scale comparable to the burst time scale. Though Nayakshin et al. (1999) were able to reproduce many characteristics in the X-ray variability for GRS 1915+105, they were unable to explain the rise/fall times or the $< 10$ s oscillations.

Yadav et al. (1999) presented a comprehensive picture for the origin of these bursts. They suggested that the peculiar bursts are characteristic of the change of state of the source. The source can switch back and forth between the low-hard state and the high-soft state near critical accretion rates in a very short time scale, giving rise to the irregular and quasi-regular bursts. It was pointed out that changes in total accretion rate cannot manifest itself in short time scales and hence the fast spectral state changes in GRS 1915+105 cannot be explained by changes in total accretion rates. Chakrabarti & Manickam (2000) provided an explanation for this remarkable observation by invoking mass loss. Unlike the canonical low-hard state where the hard power-law is due to Comptonisation, in the hard state observed during the bursts there should be an additional feature due to winds. Chakrabarti
et al. (2000) have observed subtle differences in the spectra during the bursts compared to the spectra during the long duration low-hard and high-soft states. This change is above $\sim 10$ keV where the hard component of the low state softens. This is the effect predicted in Chakrabarti (1998) where the addition of about 10% mass loss in wind has an effect of pushing the spectral cross-over point from 15-17 keV (for a 10 M$_\odot$ black hole) to higher energies.

3. Inner Disk Oscillations and Synchrotron Radio Emission

There have been attempts to connect the X-ray variability characteristics to the onset of jet emission in GRS 1915+105. Fender et al. (1999) made a detailed analysis of the super-luminal jet ejection events observed in GRS 1915+105 in 1997 October/November and detected continuous short period (20−40 minute) radio oscillations during the start of the jet emission. They proposed that these are indications of repeated ejection of the inner accretion disk, quite similar to the events seen in X-rays by Belloni et al. (1997). A causal connection between disk and jet was thus attempted. Naik et al. (2000) have reported the detection of a series of X-ray dips during a huge radio flare of strength...
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0.48 Jy (at 2.25 GHz). They argue that a large number of such X-ray dips can account for the radio flare emission.

To put such disk-jet connections in perspective, we have shown in Figure 2 (top panel) the observed ASM count rates during 1996/1997. The concurrently obtained RXTE-PCA data have been classified by Belloni et al. (2000a) and these are shown in the bottom panel of the figure, along with the 2.2 GHz radio data obtained from GBI public domain. The 1997 slow state transition is particularly interesting (see also Rao et al. 2000b).

It can be seen from the figure that the source was in a stable low-hard state up to 1997 April 25 (ASM day number 1210). The radio flux during this state is 20 – 30 mJy. This is the radio-quiet low-hard state of the source (Muno et al. 1999). The source started a steady increase in its X-ray emission with an average increase in the ASM count rate of 0.65 s\(^{-1}\) day\(^{-1}\) and reaching a count rate of 76 s\(^{-1}\) in the middle of July (day number 1290). During the beginning of the transition, the source showed several episodes of \(\alpha\) states, accompanied by brief radio flares. For more than a month the source showed several episodes of the inner disk oscillations (classes \(\rho\), \(\kappa\) and \(\lambda\)) (Yadav et al. 1999; Belloni et al. 1997). The source reached a steady high-soft state (classes \(\delta\), \(\gamma\) and \(\mu\)) when the radio emission is very low (\(\leq 20\) mJy). The ringing flares started again in the beginning of 1997 August (Yadav et al. 1999) and towards the end of this state the peculiar outbursts (class \(\beta\)) accompanied by infrared flares were observed on 1997 August 14-15 (Eikenberry et al. 1998). On September 9 the peculiar “outburst” was seen again (Markwardt et al. 1999). In October 1997 the source reached the radio-loud hard-steady state when both the X-ray and radio fluxes were high without the evidence of any oscillations. Fender et al. (1999) described this class as the “plateau” state.

From these we can conclude that the inner disk oscillations involving rapid transitions (classes \(\rho\), \(\kappa\) and \(\lambda\)) do not lead to any appreciable radio emission. Apart from the radio-loud hard state, classes \(\theta\) and \(\beta\) are associated with enhanced radio emission. Class \(\beta\) are associated with the synchrotron flares in radio (Mirabel et al. 1998; Fender & Pooley 1998) and infrared (Eikenberry et al. 1998). From simultaneous X-ray and infrared observations, Eikenberry et al. (1998) made a strong argument that the onset of radio/infrared flare is associated with the soft dip rather than the gradual change to the low-hard state. Radio oscillations on a time scale of 20 – 30 minutes are seen to be accompanied by a series of soft X-ray dips (Fig. 10, Dhawan et al. 2000), similar to the oscillations observed by Fender et al. (1999). Since the soft dip events are associated with the jet emission, Naik et al. (2000) proposed
that the huge radio flares are produced by a series of such soft X-ray dips.

Naik and Rao (2000) made a systematic study of the radio and X-ray emissions from GRS 1915+105 and found an one-to-one association between radio flares and the $\beta$ and $\theta$ classes. If the onset of a huge radio flare (signifying the emission of a superluminal ejecta) is associated with an X-ray emission characteristic observed so far, it has to be necessarily with the $\beta$ or $\theta$ classes. Belloni et al. (2000b), however, associate the change of state with the radio emission rather than the peculiar dips seen in these two classes. A continuous X-ray monitoring during a radio flare should clarify this question.

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