Inner disk oscillations

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Abstract. The RXTE observations of GRS 1915+105 have given a new impulse to the study of spectral and timing properties of the X-ray emission of black hole candidates. At variance with any other known source, GRS 1915+105 shows dramatic changes on time scales as short as a tenth of a second. These changes are associated to marked spectral changes which have been interpreted as changes of the observable inner radius of the accretion disk. I review the existing results and discuss the current evidence for such disk oscillations. Independently of the precise theoretical models, the detailed study of these fast variations can provide an extremely valuable insight on the accretion processes onto black holes. Making use of these results, I compare the properties of GRS 1915+105 with those of other black hole candidates.

Keywords: black hole candidates, Microquasars, accretion disks

1. Introduction: black hole candidates

In the recent years, a classification scheme for the X-ray emission of black hole candidates has emerged. From the timing and spectral properties, four separate states (plus the quiescent state for transient systems) have been identified, probably in dependence of the accretion rate level (see van der Klis 1995). Unfortunately, all known persistent sources, Cyg X-1, GX 339-4, LMC X-1 and LMC X-3, show state transitions very rarely, making the accumulation of extensive datasets on different states difficult. Transient systems are more promising, but their transient nature limits the number of states and state transitions that can be observed from one system, and the comparison between different systems is always problematic.

The spectral properties of black hole candidates are usually characterized in terms of a double-component model. The first component is thermal and (when present) contributes mostly to the flux below 10 keV. It is commonly interpreted as emission from an optically thick accretion disk (Mitsuda et al. 1984). The second component is much harder and extends above 10 keV. In its simple form, it can be approximated as a power law, although more sophisticated models are often required (see e.g. Frontera et al. 2000). An attractive feature of the optically thick disk model, the so-called disk-blackbody, is that one of its parameters is the value of the inner radius of the accretion disk. Therefore, the application of this model can in principle yield the
measurement of this fundamental parameter, although a precise value depends on the distance and the inclination of the system. This model became rather popular when a number of black hole systems showed a rather constant inner disk radius, around 20-30 km, despite large changes in accretion rate (see Tanaka & Lewin 1995). Although this model is simplified and leads to an underestimate of the values of the radii, it can detect large variations in the inner radius of the disk (see Merloni, Fabian & Ross 2000).

2. GRS 1915+105: inner disk oscillations

The galactic Microquasar GRS 1915+105 is known to exhibit dramatic variability in the soft (1-20 keV) energy band (see Greiner, Morgan & Remillard 1996; Belloni et al. 2000) and since its appearance in 1992 it has remained active up to the time of writing. This variability is accompanied by strong spectral changes (Greiner, Morgan & Remillard 1996; Belloni et al. 1997a,b; Muno, Morgan & Remillard 1999), providing an ideal system to study spectral transitions in a black-hole candidates: the source is always observable and significant spectral variability is present on very short time scales. At the same time, a complex behavior is observed in the power density spectra of the source (see Rao, this volume). Right: corresponding

Belloni et al. (1997a,b) proposed a model for the observed spectral variations, based on fits to RXTE/PCA data with the approximated spectral shape described above. They interpret the observations as the onset of a thermal-viscous instability, during which the innermost part
of the accretion disk becomes unobservable and is slowly refilled from the outer parts. This interpretation is based on the measurement of a variable inner disk radius from energy spectra (see Figure 1) and is supported by the observation of the expected dependence between size of the unstable region and refill time (Figure 2). The observed radius variations are too large to be attributed to spurious effects due to the approximate form of the model. This is what I will refer to as ‘inner disk oscillations’. The modeling by these authors was rather qualitative (with the exception of the estimate of the refill time scale), but other authors have developed more accurate models for this process (Szuszkiewicz & Miller 1998, Nayakshin, Rappaport & Melia 2000, Janiuk et al. 2000).

3. Spectral states of GRS 1915+105

Belloni et al. (2000) analyzed a large number of RXTE/PCA observations of GRS 1915+105 and obtained a subdivision of the observed phenomenology into 12 separate classes. From this classification, they identified three basic states, the alternation of which cause all of the observed variability. The three classes, called A, B and C, are shown schematically in Figure 3, which represents a color-color diagram (both colors increase with increasing hardness of the spectrum).

These states correspond to the three states already identified by Markwardt, Swank & Taam (1999). Class B correspond to the “normal” state of a black hole candidate at high accretion rate (the very high state), with an optically thick accretion disk extending down to the last
Figure 3. Schematic color-color diagram showing the basic A/B/C states and their observed transitions (from Belloni et al. 2000).

stable orbit and a steep power-law component. State C corresponds to the instability periods: the accretion disk stops at a larger radius than in state B, while the power law component is harder. State A is a new state, not recognized earlier. It corresponds to an accretion disk like in state B, but with a lower temperature, and therefore lower local accretion rate. The relatively fast transition time between A and B is consistent with being the viscous time scale at the innermost stable orbit around the black hole. The observed variability consists of transitions between these three states: all possible transitions between two of the states are observed, with the exception of C to B transitions, of which no example has been found.

There are intervals of time, even as long as a month, when the source is found only in state C. These are the ‘plateau’ intervals observed in the radio band (see Fender 1999). These are consistent with being long instability intervals, when a large missing inner disk is slowly refilled at a lower external accretion rate (Belloni et al. 2000). On the other hand, there are very fast variations as well. During some observations, variability of a factor of five in 0.1 seconds has been observed, corresponding to fast A–B/B–A transitions (Belloni et al. 2000).
4. Timing properties

It is important to connect what is observed in the time domain and the state transitions described above. As a first step, I consider the three types of QPOs observed in GRS 1915+105:

- 1-10 Hz QPO: (see Rao, this volume). This QPO is only observed during state C. Its central frequency varies systematically with time, count rate and hardness. Since state C is the only state when systematic changes in the inner disk radius are observed, it is natural to associate this oscillation to the inner radius, although often the missing part of the disk is so large that no disk component is observed directly, indicating that the QPO must be related to the power law component.

- 67 Hz QPO: This QPO appears only during state B. Its high and rather constant frequency and its association with a state with small (and possibly constant) inner disk radius also point to a connection to the inner disk radius. It is interesting to note that this QPO is not observed in all state-B intervals, indicating that there must be another parameter involved in its production.

- Low-\(\nu\) QPO: These oscillations, in the range 10-100 seconds (see Morgan, Remillard & Greiner 1997) are the regular transitions between states that are often observed. The instability model provides an interpretation for the variability, but does not cast light on why the light curves are so regular.

There is another important point about the timing properties of the source. Looking at the light curves (see Belloni et al. 2000), one notices not only that their time structure is very complex, but also it often repeats in an almost undistinguishable way, so that all observations can be grouped in twelve classes. As mentioned above, there is no clear explanation for why the structure of the light curves is the observed one. More than this, sometimes even the finest structures of the light curves repeat at a distance of years (see Figure 4). The basic question that need to be answered are: why do the light curves have those complex and repeatable shapes, and why do the light curves have only those complex shapes, with only a few possibilities to choose from? Answering these questions could provide crucial information about the accretion phenomenon.
5. A unique source?

Another important question is: are there other sources that show the same phenomenology seen here? To this date, the answer is: the C-state events (the instability) are observed only in GRS 1915+105, but A–B transitions have been observed in other systems, namely 4U 1630-47 and GRO J1655-40 (Trudolyubov, Borozdin & Priedhorsky 2000, see Figure 5). Possibly, the dips and the so-called flip-flops seen earlier in GX 339-4 (Miyamoto et al. 1991) are also of the same nature. It seems clear that this type of fast (and often very regular) temperature oscillations are more common among bright black hole candidates, although their origin is still unknown. The question of why the C-state instability is observed only in this source is still basically unanswered. Possibly, this type of instability appears only at very high levels of accretion rate, which would then be reached only by GRS 1915+105. The observation of the same phenomenon in another source would greatly help to understand this issue.

6. Relation to the canonical black hole states

An important point is the comparison between the A/B/C states of GRS 1915+105 and the four canonical black hole states mentioned above. It is tempting to associate state C with the low/intermediate state (hard spectrum flat-top noise and QPO in the power spectrum), state B with the very high state (strong disk component, weaker noise...
level), and the A state with the high state (cooler disk component, low noise level). However, as mentioned above, the instability related to the C state is not observed in other sources. It is more likely that the similarities between the properties of GRS 1915+105 and the canonical black hole states are not indicative of them being the same, but rather of them looking the same. In other words, the onset of the instability in GRS 1915+105 influences the accretion structure in a way that makes it mimic the properties of the canonical states observed in “normal” sources.

7. Inner disk oscillations and radio jet ejection

The X-ray phenomenology described above has been positively linked to the variability observed in the radio band, and major events have been associated to the emergence of superluminal radio jets. This topic is treated by other authors in this volume. Here it is important to stress that the analysis of simultaneous X-ray/radio observations has shown that radio flares seem to be associated only to state C events, and therefore to the inner disk oscillations, while observations containing only states A and B do not correspond to significant radio detections of the source (see Klein-Wolt et al., this volume). However, the presence of
this instability has not yet been observed in the other galactic sources showing jet ejection in the radio.

8. Conclusions

GRS 1915+105 is the only source up to now which can provide a large number of spectral transitions, enabling us to study different states of one source without having to wait for years. The most important of these transitions do not involve the canonical states of black hole candidates, but are associated to an instability of the innermost region of an optically thick accretion disk, which causes its inner parts to be evacuated and refilled on the local viscous time scale. Other variations observed in this source can be linked to those observed in other sources, strengthening the connection between this unique system and more conventional ones. On the X-ray side, it is now important to examine the spectral/timing behavior of GRS 1915+105 in more detail (see Migliari, Vignarca & Belloni, this volume), in order to provide a more complete phenomenological picture for further theoretical work. Modeling of the X-ray properties of GRS 1915+105 is at the moment the most promising way to make significant progress in the understanding of accretion onto black holes.

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