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Near to the Black Hole Horizon in GRS 1915+105

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Abstract. The superluminal *microquasar* GRS 1915+105 is, among the candidate black hole binaries in our Galaxy, certainly the one with the most exotic behavior. It shows very strong variability at all timescales, but also its spectral properties justify non-trivial interpretations. In the X-rays, a strong and broad iron line has been detected at $E \sim 6.4$ KeV in two observations of the satellite *BeppoSAX*, with a distorted profile that can be well modelled only if general-relativistic effects in the very vicinity of the event horizon are considered. Observations with X-ray satellites of the newest generation, like *XMM-Newton*, are of great interest in order to understand the possible links between the iron feature and other spectral components, that is to get information on the most intime region around the black hole as well as on the accretion mechanism which is at play.

Key words. black hole physics - relativity - line: formation - line: profiles - X-rays: binaries - X-rays: individuals: GRS 1915+105

1. Introduction

During two *BeppoSAX* observations of the well-known superluminal *microquasar* GRS 1915+105 – which took place on April 19-20, 1998, and April 21-22, 2000, respectively – intense, broad and asymmetric iron Kα fluorescent lines were detected, most likely originating in a relativistic disc around a central black hole (BH; Martocchia et al. 2002, 2004,e.g. Fig. 1).

The presence of a BH at the center of GRS 1915+105 is confirmed also by the mass function of this system. Since the interstellar absorption on the line of sight of GRS 1915+105 (which is located very near to the galactic plane) is very strong, the source counterpart was discovered only via infrared observations, yielding evidence that GRS 1915+105 belongs to the class of low-mass X-ray binaries (LMXBs). The same infrared observations allowed to constrain a mass of the central compact object $M_{\rm c} = 14 \pm 4 M_{\odot}$, i.e. well above the standard neutron star mass limit (see Greiner et al. 2001,and references therein). GRS 1915+105 is thus believed to host a BH with a gravitational radius $r_g = \frac{GM}{c^2} \sim 21$ km.

However, the issue of the central BH spin remains open. In the case of the mentioned *BeppoSAX* observations, we could profit of the iron line diagnostics, which allows to determine the accretion disc innermost stable orbit

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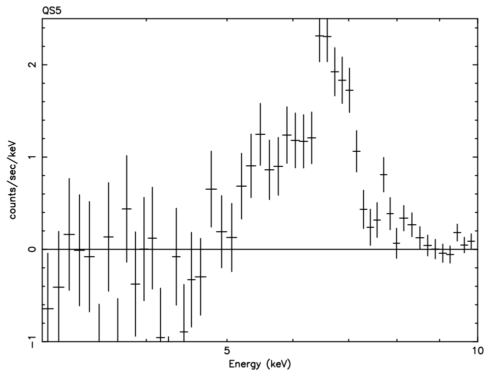

Fig. 1. Residuals at the iron line energy, for the second time interval out of six selected in the 1998 *BeppoSAX* observation. The relativistic line model normalization has been put to zero for illustration purposes (from Martocchia et al. 2002).

$r_{\rm ms}$, a known function of J/M in Kerr metric, customarily put equal to the inner boundary of the optically thick portion of the disc itself. This therefore appears as one of the interesting cases in which the relativistic iron line diagnostics can be used to unveil the characteristics of the compact object hosted at the center of a X-ray binary.

2. Relativistic Iron Lines in Galactic BH Candidates

A broad iron line in the spectrum of a X-ray binary can have a disc or a jet origin. For the sake of simplicity we will not discuss the second case here. If the line is emitted from the innermost part of the disc, its profile carries the general-relativistic (GR) imprints of the strong gravitational potential well in the vicinity of compact object. In the case of candidate BHs, this can even allow to estimate the BH spin parameter (see e.g. Fabian et al. 1989; Tanaka et al. 1995; Martocchia et al. 2000, 2002,for references on the GR line model) for references on the GR line model).

On the other hand, in galactic stellar-mass sources the ionization of the accreting flow is thought to be much more relevant than in Active Galactic Nuclei (AGN) because of the much larger disc temperature in stellar size objects; this implies a blue-shift of the line centroid energy, but may sometimes result in fluorescent emission being much less effective. Moreover, finding the line out of the thermal emission high-energy tail can be difficult in galactic BH candidates. Further, the non-negligible X-ray variability of such sources, which reflects rapid changes in the physics and geometry of the accretion/ejection phases, also causes the iron emission to be non-steady, and even non-detectable in many situations: the line could disappear as a consequence of the disc blowing up.

Indeed, the iron line in GRS 1915+105 is usually not very intense in *BeppoSAX* observations (EW $\sim$ 20 $\div$ 30 eV), so that its profile is generally difficult to study in detail. But this source is a notoriously variable one, with the innermost part of the accretion disc most likely being blown-up and/or becoming optically thin for a relevant fraction of the time. We also had to select appropriate time intervals, out of both observations, in which the variability is less dramatic, thus the source physical/spectral state is better defined.

While *ASCA* SIS data of GRS 1915+105 only showed absorption features (Kotani et al. (2000)), the possible presence of a narrow line in *Chandra* data, likely emitted by neutral iron in a "low-hard" source state, has been reported by Lee et al. (2002). *Rossi-XTE* PCA data are generally well-fitted including a broad iron line component (see e.g. Done et al. 2004), but the energy resolution of this instrument does not allow to discriminate among different line models. There is only another case, to our knowledge, in which the iron line has been detected so prominent, broad and asymmetric in this source: that is in *ASCA* GIS archive data, recently analyzed by Miller et al. (2004c). The same authors found that *ASCA* GIS data of a few interesting galactic BH sources – including the other superluminal *microquasar* GRO J1655-40 – also show iron line profiles with similar properties (see Fig. 2). The most famous galactic BH candidate, Cygnus X-1, showed an intense and broad iron line too, with an extremely red-shifted profile also visible in

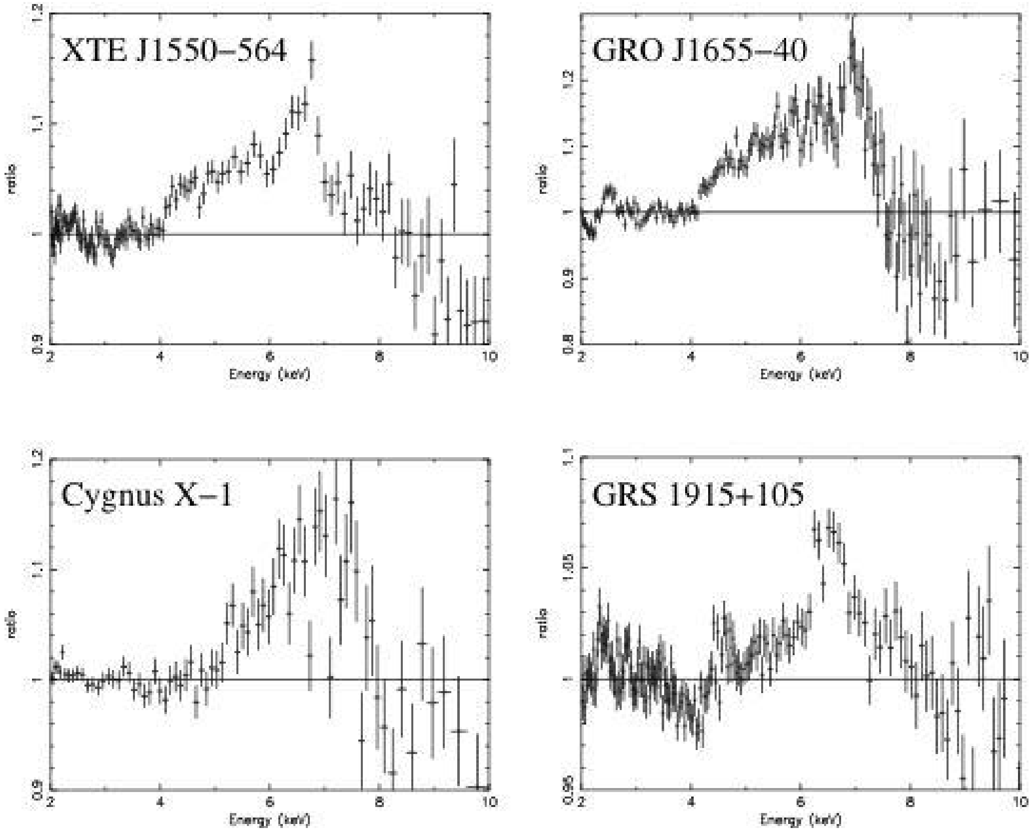

Fig. 2. Broad, relativistic iron line profiles in *ASCA* GIS data of GRS 1915+105 and other galactic candidate BH sources (from Miller et al. (2004b)).

BeppoSAX and *Chandra* data (Frontera et al. 2001; Miller et al. 2002b). The profile is not double-peaked, which in the disc assumption may be attributed to a low source inclination.

In the cases of XTE J1650-500 (Miller et al. 2002a; Miniutti et al. 2004) and GX 339-4 (Miller et al. 2004a,b) very broad, skewed lines are seen, best-fitted with a canonical Kerr innermost stable orbit and a very steep emissivity profile. Broad lines, best-fitted with a relativistic disc model, have been observed also in V4641 Sgr and XTE J2012+381. Other BH candidate spectra have been studied thanks to the satellite *Rossi-XTE* alone: in these cases more caution is necessary, since this satellite's energy resolution is not enough to measure GR distortions of spectral features in detail. However, broad features have been detected e.g. in GRO J1655-40 and XTE J1748-288. In other sources, the lines and their profiles are rather interpreted as products of ejected material; in some cases, their real nature has to be better intestigated.

3. The Relativistic Disc in GRS 1915+105

Interestingly, most of the observed broad, intense Fe lines in galactic BH candidates have beed detected during "very high"/"intermediate" or "quiescent" (low/hard) spectral states. A plausible explanation for this has still to be found: to produce the line, the accretion disc must efficiently reflect primary photons, even at the innermost radii.

In the *BeppoSAX* 1998 observation of GRS 1915+105 we register a high luminosity, of the order of 10^8 in cgs units (unabsorbed), and a steep powerlaw ($\Gamma \sim 2.65$), with a cut-off at rather low energies ($E_{\rm cut} \sim 25$ KeV). In the 2000 observation we have a harder continuum ($\Gamma \sim 2.3$, $E_{\rm cut} > 70$ KeV), but thermal emission is clearly seen, and "cold" reflection is better constrained ($R \sim 1$). Both observations may correspond to "intermediate" or "very high" states, with Comptonization tails originating from the disc blackbody seed photons.

This is in agreement with the conclusions of Reig et al. (2003): although the phenomenology of GRS 1915+105 has been usually (on the base of the hardness ratio and the position in the colour-colour diagram) described in terms of three spectral states, named A, B and C (the latter being "quiescent" and "jet-dominated", e.g. Belloni et al. 1997), in fact several source properties always correspond to the canonical *very high state* of galactic BH sources. I.e., the source never escapes the upper, horizontal branch of the hardness vs. intensity diagram (see Fig. 10 in Belloni 2004). Also Done et al. (2004) compared the evolution of spectral shape with luminosity in this source with that of other BH candidates, by taking advantage of the many *Rossi-XTE* PCA observations of GRS 1915+105, from 1996 to 2000, and confirmed that this source *never* goes into the classic "low/hard" or "high/soft" states. Its high luminosity is due to an accretion rate which is near to the Eddington value all of the time, while its unique limit-cycle variability (e.g. Belloni et al. 1997) appears when the source radiates at super-Eddington luminosities.

These characteristics can be related to the binary's evolutionary state: the giant companion star and the long orbital period (33.4 days, by far the longest of any LMXB: Greiner et al. 2001) indicate that the Roche lobe overflow occurs in a very wide binary. The cause of all the unique long as well as short-term variability of GRS 1915+105 is then linked to the evolution of the huge disc structure, which can contain enough material to mantain nearly-Eddington accretion rates over timescales of several years.

It will be necessary to wait until the next generation of disc models is developed in order to have a reliable description of such a huge disc structure. As far as the disc thermal emission is concerned, the available fitting models are not adequate, either. BH mass estimates inferred using the thermal luminosity are physically unplausible, because of two main reasons: first, current thermal emission models, even if based on post-Newtonian corrections, are not able to properly describe radiation transfer very near to the event horizon; second, Comptonization of the disc thermal component must be accounted for, too.

Also Quasi Periodic Oscillations (QPOs) have been observed in the high-energy power spectra of GRS 1915+105, in a wide range of frequencies (0.001 ÷ 67 Hz, e.g. Morgan et al. 1997). The fact that the highest frequency (67 Hz) does not change much with time is consistent with the idea that it is linked with $r_{\rm ms}$. This has been also used to derive the spin parameter of GRS 1915+105 (see e.g. Varnière et al. 2002). However, QPO frequencies must be affected by GR effects, too: in the framework of the relativistic precession model (Stella et al. 1999) and using the observed mass values, Strohmayer (2001) estimated that the BH spin in GRS 1915+105 should approach the Kerr maximal value, being higher than in GRO J1655-40 (a very similar source). However, a self-consistent interpretation of QPOs in the mentioned "huge disc" scenario is yet to come.

4. Iron... and More

Done et al. (2004) also confirm the presence of "cold" disc reflection in the X-ray spectra of GRS 1915+105, and fit the residuals at $E \sim 6.4$ KeV with broad and relativistic line models.

Fully-relativistic routines are now available (e.g. Martocchia et al. 2000, 2002; Dovčiak et al. 2004) to reproduce the GR distortions which affect all disc line and reflection components due to the extreme spacetime curvature near the event horizon of a spinning BH. The Fe Kα fluorescent emission feature detected in both the 1998 and 2000 *BeppoSAX* observations of GRS 1915+105 is strong (EW ~ 150 eV), broad and asymmetric, most likely emit-

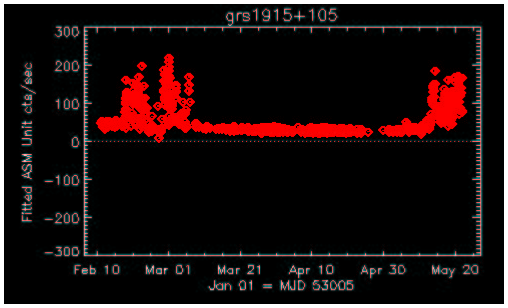

Fig. 3. The spring 2004 "plateau" state of GRS 1915+105, as plotted by the online *Rossi-XTE* ASM Weather Map interface.

ted from neutral or low ionized iron. In the case of the 1998 observation we found evidence of emission from a region of the disc which is near, but still outside the Schwarschild innermost stable orbit; on the other hand, in the 2000 spectrum emission from $r < 6r_g$ (the last stable orbit in Schwarzschild metric) is compatible with the data, even if the results of our data analysis do not allow a firm conclusion on this regard. Emission from inside $6r_g$ may indicate a Kerr spacetime, i.e. that a rotating BH is hosted at the center of the system. Of course, the disc parameters are somewhat dependent on the adopted model for the continuum, and must be taken with caution. Since the BH spin stays constant between the two observations, differences in the innermost emitting radii must reflect changes in the accretion flow.

A dedicated *XMM-Newton* observation of GRS 1915+105, to study the iron line profile with enhanced spectral resolution and sensitivity, was proposed in AO2 by this Author and collaborators, and could be finally started on April 17, 2004. The observation was triggered by the occurrence of a "plateau" state of the source: this state is similar to what occurred during the *BeppoSAX* 1998 observation, but it was requested also in order to have the source in a "less dramatic" variability state, and at a lower flux level to minimize technical problems due to instrumental pile-up and telemetry. For the latter reason we also planned to observe in Timing Mode. Both (variability and flux) conditions were met during the long "deep" state of the source, also characterized by a more intense radio emission, which lasted several weeks during the spring 2004 (Fig. 3; see e.g. http://www.mrao.cam.ac.uk/~guy/ for some radio band lightcurves of GRS 1915+105 during the same period). However, the source counts registered on April 17 were still at the limit of the technical feasibility, therefore a second part of the observation was performed on April 21, 2004 (precisely during this Conference!), this time in Burst Mode.

Interesting results are expected from the analysis of these data, which should also allow to investigate the lower energy X-ray spectrum: thanks to the unprecedented energy resolution of the RGS cameras, subtle details of the emission and absorption features in the 0.3–2.0 keV band can be analyzed. This is particularly important in such a heavily absorbed source like GRS 1915+105. Its complicated, resonant and over-abundant absorption structure has been already seen with *ASCA* (Kotani et al. 2000), *Chandra* (Lee et al. 2002) and *RXTE* (Done et al. 2004); the column density parameter is $n_H \sim 5.45 \times 10^{22}$ cm^{-2} in the 2000 *BeppoSAX* observation. But, even more interestingly to our aims, there have been claims in the past years about the possibility of detecting relativistic broadening also in several soft X-ray spectral features, like Lα emission lines of O VIII, N VII, and C VI, which are sometimes better fitted than absorption features to *XMM-Newton* RGS data of some AGN showing relativistic iron lines, too (MCG–6-30-15, MKN 766: e.g. Mason et al. 2003; Branduardi-Raymond et al. 2001).

Therefore, GRS 1915+105 data collected by RGS as well as EPIC cameras onboard *XMM-Newton* can yield very important information: they can help to look into the innermost regions of this binary system. All results will then be matched together, to provide a self-consistent physical picture of the accretion flow at just a few gravitational radii, i.e. extremely near to the BH event horizon

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