Iron Line Diagnostics for the GRS 1915+105 Black Hole

A. Martocchia\textsuperscript{a} *, G. Matt\textsuperscript{a}, V. Karas\textsuperscript{b}, T. Belloni\textsuperscript{c}, M. Feroci\textsuperscript{d}

\textsuperscript{a} Dip. di Fisica "E. Amaldi", Terza Università, via della Vasca Navale 84, I–00146, Roma, Italia
\textsuperscript{b} Astronomical Institute of the Charles University, V Holešovičkách 2, CZ–180 00 Praha, Czech Republic
\textsuperscript{c} Osservatorio Astronomico di Brera, via E. Bianchi 46, I–23807 Merate, Italy
\textsuperscript{d} IAS/CNR, Area di Ricerca di Tor Vergata, Via Fosso del Cavaliere 100, I–00133 Roma, Italy

The properties of the broad Fe line detected in two \textit{BeppoSAX} observations of the microquasar GRS 1915+105 are summarized.

1. INTRODUCTION

Martocchia et al. (2002, Paper I \textsuperscript{5}) and Martocchia et al. (2003, Paper II \textsuperscript{6}) reported the discovery of intense iron K\textsubscript{α} fluorescent emission in two \textit{BeppoSAX} observations of the microquasar GRS 1915+105, which took place respectively on April 19-20, 1998, and April 21-22, 2000. During these observations the Fe line is broad and asymmetric, best fitted with a relativistic disc model (see e.g. \textsuperscript{2}, \textsuperscript{8}, \textsuperscript{4} and Paper I for references on the relativistic line model).

These are the only two cases, to our knowledge, in which the iron K\textsubscript{α} line is so prominent in this source. The fact that the line is not always such strong in GRS 1915+105 observations should not surprise, since finding the line out of the thermal emission high-energy tail can be awkward in galactic Black Hole (BH) candidates, because of the high disk temperature. Nevertheless, strong, broad, possibly relativistic iron K\textsubscript{α} lines have recently been detected in various spectra of galactic BH candidates, e.g. Cyg X-1, XTE J1550-500, XTE J1550-564, V4641 Sgr, GRO J1655-40, XTE J2012+381, GX 339-4, XTE J1748-288, XTE J1908+094. They may help estimating the rotation parameter of the BHs hosted at the center of these sources by means of the iron K\textsubscript{α} diagnostics.

2. THE SOURCE

GRS 1915+105 is a superluminal jet source, well-known since its discovery by the \textit{WATCH} experiment on \textit{Granat} \textsuperscript{1}. The source distance is about 10 kpc, and its inclination – based on observations of its jets – 70 degrees. The optical counterpart was found only recently, via infrared observations, yielding evidence that GRS 1915+105 belongs to the class of low-mass X-ray binaries; the same observations allowed to determine the mass of the central compact object, which has been constrained to $M_c = 14 \pm 4 M_\odot$, i.e. well above the standard neutron star mass limit (see \textsuperscript{3} 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 two \textit{BeppoSAX} observations here discussed, we could profit of the Fe line diagnostics, which allows to determine the accretion disk innermost stable orbit $r_{\text{ms}}$, a known function of $J/M$ in Kerr metric, customarily put equal to the inner boundary of the optically thick portion of the disk itself.

GRS 1915+105 is a notoriously variable source, with the inner accretion disk being blown-up and becoming optically thin for a relevant fraction of the time. This is one more reason for the line not
to be always visible in *BeppoSAX* observations. We had to select appropriate time intervals, out of both observations, in which the variability is less dramatic.

3. **DATA ANALYSIS**

Spectral fits have been performed with the XSPEC software package. We assumed an optically thick, neutral, and geometrically thin Keplerian accretion disk with solar elemental abundances. For both data sets, results of a preliminary fit showed that the dependence of the disc emissivity on the radius is rather flat: we assumed a phenomenological dependence $\sim r^{-2}$. “Cold” absorption was also included: its column density parameter $n_H$ always stabilizes at about 5.4 and $5.45 \times 10^{22}\text{ cm}^{-1}$, in the two observations respectively; we thus choose these as fiducial values.

3.1. **First *BeppoSAX* observation: April 19-20, 1998 (Paper I)**

This observation started at 11:33:19 UT and ended on the next day at 20:14:52 UT. Out of the entire $\Delta t \sim 120$ ks, six time intervals of $\sim 2000$ s each were sorted out where the source variability is less pronounced. These are six orbits in which the source is in a “quiescent” state. Data from the LECS, MECS and PDS instruments have been used in the intervals 0.1–4, 1.7–10 and 15–150 keV, respectively. The basic ingredient to model the continuum is a powerlaw with cut-off. As a model for the locally emitted fluorescent and reflection features we initially considered numerically computed spectra, including the Fe line and the underlying reflected continuum derived from Monte Carlo computations and processed through our additive routine *kerrspec*. However, we verified that the model is quite insensitive to the Compton-reflected emission: to save computational time we adopted for it a simple, non-relativistic model (*pexrav* in XSPEC), and used *kerrspec* only to fit the line profile.

We applied these ingredients on MECS and PDS data only. The iron line parameters do not significantly change with more refined assumptions for the continuum, for instance accounting for LECS data and including a multicolor blackbody component (*diskpn*). Indeed, the disc thermal emission is not clearly recognizable. Furthermore, the bestfit disk temperature comes out unrealistically high ($kT \sim 3.3$ keV), while the BH mass results far too small from a physical point of view. These facts indicate that the standard interpretation of the continuum is not fully appropriate here. Here are the bestfit parameters: $F_{2-10}$ keV $\sim 1.8 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$; $\Gamma \sim 2.6 \div 2.7$; $E_{\text{cut}} \sim 25$ keV. The reflection parameter $R$ is not well constrained and can vary from $\sim 0.15$ up to $1.2 \times 2\pi$. The innermost line-emitting radius $r_{\text{in}}$ stays always above $6r_g$ (from $\sim 7.8r_g$ in the fifth interval up to $\sim 79r_g$ in the second one); the Fe line equivalent width (EW) is much larger than 100 eV in all cases, up to 300 eV in one interval.

Even though the $\chi^2$ statistics is not very good – mainly due to the difficulty in modeling the continuum components – the distorted profile (cp. Fig. 1) is always much better fitted with a relativistic line than with a gaussian. We therefore infer that the relativistic solution for the iron line, besides being the most natural physical explanation for the very broad line observed, does not depend from the choice of the continuum model.
3.2. Second BeppoSAX observation: April 21-22, 2000 (Paper II)

In this case we analyzed separately two selected – “lower” and “higher flux” – spectral phases, lasting $\sim 10$ ks each, out of the entire (19:56:55–11:16:55 UT) observation. Only data from the MECS and PDS instruments were available, and were used in the same energy intervals as above. The flux is $F_{2-10}$ keV $\sim 0.7$ and $1.1 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, in the two states respectively. Again, we started our data analysis using a powerlaw with cutoff, disk multi-blackbody emission and Compton reflection “hump”. Contrary to the 1998 observation, thermal emission from the disk is not negligible this time. Broad and skewed residuals are apparent around 6.4 keV. The Fe feature is unphysically broad when modelled with a bare Gaussian ($\sigma \sim 2$ keV, $\chi^2_{\text{red}} > 2$), suggesting relativistic broadening. We thus tried with a fully relativistic model $\text{wabs} \ast (\text{diskline} + \text{diskpn} + \text{refsch})$ where $\text{refsch}$ accounts for relativistic distortions in the reflected continuum. Since on this way the best-fit innermost line-emitting orbit always results to be equal to the inner hard limit $-6r_g$, the last stable orbit in Schwarzschild metric – it has been straightforward to test the spinning BH assumption with these data. We employed the Kerr line model $\text{kerrspec}$ (cp. Paper I) to replace $\text{diskline}$. Best-fit parameters are shown in the Table. The iron line rest energy is $E_0 \equiv 6.4$ keV. The value of the farthest emitting radius $r_{\text{out}}$ is not well constrained by the iron line models, and always tends to the outer hard limit set by the model itself.

4. DISCUSSION

The Fe K$\alpha$ fluorescent emission feature detected in both 1998 and 2000 BeppoSAX observations of the microquasar GRS 1915+105 is strong, broad and asymmetric, best-fitted with a relativistic disc model. The line is emitted from neutral or low ionized iron. In the case of the 1998 observation we found evidence of emission from a region of the disk which is near, but still outside the Schwarzschild 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 $6r_g$ would 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.

Most of the observed broad, intense Fe lines in galactic BH candidates have been detected during “very high”, “intermediate” or “quiescent” 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. This is unlikely in “hard” states, since such states correspond to absent or optically-thin disks, but could be the case of “soft/high” states.

In the GRS 1915+105 1998 observation we registered very strong flux and an extremely steep powerlaw, with a cutoff at rather low energies. In the 2000 observation we have a similar powerlaw continuum, but thermal emission is clearly seen, and “cold” reflection is better
constrained. Both observations may correspond to “very high” states, with Comptonization tails originating from the disk blackbody seed photons. BH mass estimates inferred using the thermal luminosity are physically unplausible, also due to the fact that current thermal emission models are not adequate to describe radiation transfer very near to the event horizon.

More detailed discussions on the data analysis and results are reported in Paper I and Paper II. Various issues still remain open, with regard to the accretion disk geometrical and physical states. Data with enhanced spectral resolution and sensitivity are strongly needed, and will be hopefully achieved by the next observational campaigns, first of all the ones scheduled for the satellite XMM-Newton.

REFERENCES

1. Castro-Tirado A.J., Brandt S. & Lund N. (1992), IAU Circular n.5590.
2. Fabian A.C., Rees M.J., Stella L. & White N.E. (1989), MNRAS 238, 729.
3. Greiner J., Cuby J.G. & McCaughrean M.J., 2001 (2001), Nature 414, 522.
4. Martocchia A., Karas V. & Matt G. (2000), MNRAS 312, 817.
5. Martocchia A., Matt G., Karas V., Belloni T., Feroci M. (2002), A&A 387, 215.
6. Martocchia A. et al., 2003, in preparation.
7. Matt G., Perola G.C., & Piro L. (1991), A&A 247, 25.
8. Tanaka Y. et al. (1995), Nature 375, 659.

Table 1

| “Lower flux”  | “Higher flux” |
|---------------|---------------|
| “state”       | “state”       |
| \( \Gamma \)  | 2.17^{+0.05}_{-0.02} | 2.59^{+0.04}_{-0.04} |
| \( E_{\text{cut}} \) [keV] | 78.8^{+3.9}_{-4.0} | 183.7^{+4.1}_{-3.8} |
| \( R \)       | 0.92^{+0.22}_{-0.09} | 1.72^{+0.14}_{-0.03} |
| \( \xi \) (reflection) [erg cm\(^{-2}\) s\(^{-1}\)] | 10.3^{+47.0}_{-8.6} | 0.000^{+0.001}_{-0.000} |
| \( T \) (reflection) [eV] | 28.7^{+61.0}_{-10.2} | 85.1^{+49.3}_{-21.0} |
| \( T \) (blackbody) [eV] | 393^{+41}_{-37} | 1414^{+63}_{-19} |
| \( r_{\text{in}}/r_{g} \) (blackbody) | 10.0^{+0.6}_{-0.7} | 79.2^{+0.9}_{-1.4} |
| \( r_{\text{in}}/r_{g} \) (Fe K\(\alpha\)) | 3.9^{+16.6}_{-1.6} | 1.4^{+3.7}_{-0.2} |
| Fe K\(\alpha\) EW [eV] | 125 | 126 |
| \( \chi^2/dof \) | 148.2/86 | 144.9/86 |
| \( \chi^2/dof \) \( (r_{\text{in}}/r_{g} \equiv 6) \) | 148.9/86 | 154.9/86 |