2 YEARS OF INTEGRAL MONITORING OF GRS 1915+105. I. MULTIWAVELENGTH COVERAGE WITH INTEGRAL, RXTE, AND THE RYLE RADIO TELESCOPE

J. Rodriguez,1 D. C. Hannikainen,2 S. E. Shaw,3 G. Pooley,4 S. Corbel,1 M. Tagger,5 I. F. Mirabel,6 T. Belloni,1 C. Cabanac,3 M. Cadolle Bel,5 J. Chenevez,9 P. Kretschmar,5 H. J. Lehto,10 A. Paizis,11 P. Varnière,12 and O. Vilhu2

Received 2007 July 2; accepted 2007 November 29

ABSTRACT

We report the results of simultaneous monitoring observations of the Galactic microquasar GRS 1915+105 with INTEGRAL and RXTE from 3 up to ~300 keV, and the Ryle Telescope at 15 GHz. We first identify the classes of variability in which GRS 1915+105 is found, and report some direct transitions between them. The accretion ejection connections are studied in a model-independent manner through the source light curves, hardness ratio, and color-color diagrams. During a period of steady "hard" X-ray state (class $\chi$) we observe a steady radio flux interpreted as the signature of a compact jet. We then turn to three particular observations during which we observe several types of soft X-ray dip and spike cycles, followed by radio flares, corresponding to classes $\nu, \lambda$, and $\beta$ types of variability. This is the first time ejections are reported during a class $\lambda$ observation. We generalize the fact that a (nonmajor) discrete ejection always occurs, in GRS 1915+105, as a response to an X-ray sequence composed of a spectacularly hard X-ray dip terminated by an X-ray spike marking the disappearance of the emission above 18 keV. We identify the trigger of the ejection as the X-ray spike. A possible correlation between the amplitude of the radio flare and the duration of the X-ray dip is found. The X-ray dips prior to ejections could thus represent the time during which the source accumulates energy and material that is ejected later. The fact that these results do not rely on any spectral modelling enhances their robustness.

Subject headings: accretion, accretion disks — black hole physics — radio continuum: stars — stars: individual (GRS 1915+105) — X-rays: binaries

1. INTRODUCTION

Microquasars are the Galactic scaled-down versions of active galactic nuclei (AGNs; Mirabel & Rodriguez 1998). In both classes of systems, the copious emission of energy is thought to originate from the accretion of matter onto the central black hole (BH), which occurs through an accretion disk. Relativistic ejections are observed in both classes of objects, either through discrete jets or in a self-absorbed compact jet. Apart from morphological similarities, the difference of the mass of the central object leads to a higher temperature of the inner regions of the accretion disk in the Galactic sources, smaller extent of the jets, and, of high importance, smaller timescales in any of the phenomena associated with either accretion or ejection processes (Mirabel & Rodriguez 1998). As a result, microquasars are excellent labora-

dories in which to study the accretion-ejection links on timescales from seconds to days. This is done by coupling the variations seen at X-ray energies (mapping the regions closest to the compact object) to those seen at radio and infrared (IR) wavelengths (representing the emission from the jets). Such a task has been initiated in GRS 1915+105 (Pooley & Fender 1997; Eikenberry et al. 1998; Mirabel et al. 1998; Fender & Pooley 1998), and pursued in a large number of systems since then.

An extensive review on GRS 1915+105 can be found in Fender & Belloni (2004). To summarize, GRS 1915+105 hosts a BH of $14.0 \pm 4.4\ M_\odot$ (Harlaftis & Greiner 2004), it is one of the brightest X-ray sources in the sky and a source of superluminal ejections (Mirabel & Rodriguez 1994), and it has a true bulk velocity $\geq 0.9c$. From these superluminal motions an upper limit on the distance to GRS 1915+105 of 11.2 kpc could be derived (on the assumption of intrinsic symmetry in the bipolar jets; Fender et al. 1999), although a distance as low as 6 kpc (Chapuis & Corbel 2004) cannot be excluded. The source is also known to show a compact jet during its periods of low and steady X-ray emission levels (Dhawan et al. 2000).

GRS 1915+105 has been extensively observed with the Rossi X-ray Timing Explorer (RXTE) since 1996. A rich pattern of variability has emerged from these data with timescales from years down to 15 ms (e.g., Morgan et al. 1997). Belloni et al. (2000), analyzing 163 RXTE observations from 1996 to 1997, classified all the observations into 12 separate classes (labeled with greek letters) based on count rates and color characteristics. This scheme has been widely used ever since and is also applied here. The classes could be interpreted as transitions between three basic states (A–B–C), A being equivalent to the soft state, B to the soft intermediate state, and C to the hard intermediate state in the classification of Homan & Belloni (2005). These spectral changes...
are, in most of the classes, interpreted as reflecting the rapid disappearance of the inner portions of an accretion disk, followed by a slower refilling of the emptied region (Belloni et al. 1997). Note that other possibilities, such as the disappearance of the corona (Chakrabarti & Papadakis 1998), might reflect some magnetic flood scenario in which reconnection of the disk-jet relation could be studied in detail. This kind of cycle could also reflect the rapid disappearance of material from the system and were found to correlate with the disk instability, as observed in the X-ray band. This was the first time the disk-jet relation could be studied in detail. This kind of cycle could also reflect some magnetic flood scenario in which reconnection events would allow the ejection of blobs of material (Tagger et al. 2004).

While fine X-ray spectral and temporal analysis will be presented in a companion paper (Rodriguez et al. 2008), we analyze here, in a model-independent way, the multiwavelength data from our 2 yr monitoring campaign focusing on the observations during which correlated X-ray and radio variabilities are seen. We start with giving the basic properties of our INTEGRAL observations, i.e., we describe the campaign and the data-reduction processes in §2. In §§3 and 4 we describe and discuss the four observations from which strong radio/X-ray connections are observed.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Journal of the Observations

The journal of the INTEGRAL observations belonging to our monitoring campaign taken from 2004 October to 2005 December is given in Table 1, while Table 2 reports the details of our simultaneous RXTE monitoring. The daily multiwavelength light curves of GRS 1915+105 as seen by RXTE ASM (1.2–12 keV) and the Ryle Telescope (RT; 15 GHz) over the period of interest are reported in Figure 1 (January 1st 2004 is MJD 53,005). The days of our INTEGRAL pointings are shown as vertical arrows; the four bigger ones indicate the four observations whose accretion ejection properties are discussed in more detail in this paper.

### Table 1

| Observation No. | Revolution No. | ObsID     | MJD Start | MJD Stop |
|-----------------|----------------|-----------|-----------|----------|
| 1               | 246            | 0200280001| 53296.373 | 53297.584 |
| 2               | 255            | 0200280002| 53324.277 | 53325.510 |
| 3               | 295            | 0200280003| 53442.954 | 53444.149 |
| 4               | 305            | 0200280004| 53472.867 | 53474.141 |
| 5               | 315            | 0200280005| 53503.632 | 53504.869 |
| 6               | 356            | 0320020001| 53626.385 | 53627.598 |
| 7               | 361            | 0320020002| 53640.386 | 53641.580 |
| 8               | 367            | 0320020003| 53659.956 | 53660.367 |
| 9               | 368            | 0320020004| 53661.322 | 53662.131 |
| 10              | 373            | 0320020005| 53676.247 | 53677.488 |
| 11              | 379            | 0320020006| 53694.273 | 53695.469 |

Note.—The simultaneous RT observations are also indicated.

### Table 2

| Observation No. | ObsID     | MJD Start | Date       |
|-----------------|-----------|-----------|------------|
| 1               | 90105-03-02-00 | 53296.387 | 2004 Oct 18 |
| 2               | 90105-03-03-00 | 53296.593 | 2004 Oct 18 |
| 3               | 90105-03-04-00 | 53296.561 | 2004 Oct 18 |
| 4               | 90105-03-05-00 | 53296.728 | 2004 Oct 18 |
| 5               | 90105-03-06-00 | 53296.794 | 2004 Oct 18 |
| 6               | 90105-03-07-00 | 53297.039 | 2004 Oct 18 |
| 7               | 90105-03-08-00 | 53297.370 | 2004 Oct 18 |
| 8               | 90105-03-09-00 | 53297.440 | 2004 Oct 18 |
| 9               | 90105-03-10-00 | 53297.508 | 2004 Oct 18 |
| 10              | 90105-03-11-00 | 53297.676 | 2004 Oct 18 |
| 11              | 90105-03-12-00 | 53297.845 | 2004 Oct 18 |

2.2. INTEGRAL Data Reduction

Our monitoring makes use of the INTEGRAL Soft Gamma-Ray Imager (ISGRI; Lebrun et al. 2003)—the low-energy detector of the Imager On-Board INTEGRAL (IBIS)—to cover the 18 to ~300 keV energy range, and the X-ray monitors JEM-X (Lund et al. 2003) to cover the 3 to 30 keV energy range. Both...
corrected light curves we produced softness ratios (SRs) defined in Belloni et al. (2000) from the Proportional Counter Array (PCA). These bands are 2–5.7 keV (channels 0–13, PCA epoch 3), 5.7–14.8 keV (channels 14–35), and >14.8 keV (channels 36–255). The colors were defined as HR1 = 5.7/14.8/2–5.7 keV and HR2 = 14.8–60/2–5.7 keV. The shift of gain between the different epochs of PCA leads to different absolute values of the count rates, hardness ratios (HRs), and position in the color-color (CC) diagrams, but the general shape of a given class is easily comparable to those of epoch 3 (Belloni et al. 2000), and therefore allowed us to easily identify the class of variability in each observation. Light curves with 16 s resolution were extracted from standard 2 data between 2 and 18 keV. These were directly compared to the 3–13 keV and 18–50 keV light curves extracted from the INTEGRAL data. All of these light curves were corrected for background, using the latest PCA background models available for bright sources.

2.4. Ryle Telescope Observations

The observations with the RT followed the scheme described by Pooley & Fender (1997). Observations of Stokes’ I + Q parameters were interleaved with those of a nearby phase calibrator (B1920+154); the flux-density scale was set by reference to 3C 48 and 3C 286 and is believed to be consistent with that defined by Baars et al. (1977). The data are sampled every 8 s, and 5 minute averages are displayed in this paper. Figure 1 shows the 15 GHz long-term light curve of GRS 1915+105.

3. ACCRETION EJECTION LINKS AND THE PRESENCE OF X-RAY CYCLES

Although the classification of the X-ray classes is purely phenomenological, we think it is rather important since it helps when referring to a given observation. Furthermore, the succession of classes, their relation with the radio behavior, and the pattern of state transition through a single class probably hides rich physical phenomena related to the accretion and ejection mechanisms. Hence, we feel it is important to report the identification of all classes and the possible transitions we observed during our campaign. Since it is not the core of our paper, however, this is given in the Appendix. The classes of variability identified during each observation are reported in Table 3. In the following we focus on the accretion ejection links of observations (Obs.) 1, 2, 4, and 5 with particular emphasis on the intervals that respectively belong to classes ν, λ, χ, and β during the times we have simultaneous radio and X-ray coverages (see Appendix).

3.1. Observation 1: Class ν

As can be seen on at least Figure 2 on two occasions, a sequence of >100 s long X-ray dip ended by an X-ray spike (hereafter cycles) were followed by radio flares indicative of ejection of material (e.g., Mirabel et al. 1998). The cycles are all well defined above 18 keV (Fig. 2), with almost identical patterns as in the soft X-rays, although the dip and spike have a less marked amplitude. A notable difference with the soft X-ray light curve, however, is the presence of a short dip close to the spike. The shapes of the two radio flares are similar (Fig. 2). To estimate...
| Observation No. | Revolution No. | Source                  | Flux (counts s⁻¹) | 20–40 keV Significance | Classes |
|-----------------|----------------|-------------------------|-------------------|------------------------|---------|
|                 |                |                         | 20–40 keV         | 40–80 keV              |         |
| 1…………………..| 246            | GRS 1915+105            | 37.5              | 11.0                   | 669     | \(\nu, \rho\) |
|                 |                | H 1907+097\*            | 2.7               | ...                    | 49      |         |
|                 |                | 4U 1909+07              | 1.2               | 0.34                   | 20      |         |
|                 |                | Ser X-1                 | 1.4               | ...                    | 13      |         |
|                 |                | XTE J1855–026           | 1.3               | ...                    | 6.4     |         |
|                 |                | SS 433                  | 0.4               | ...                    | 6.1     |         |
| 2…………………..| 255            | GRS 1915+105            | 19.5              | 5.4                    | 355     | \(\mu, \lambda, \delta\) |
|                 |                | H 1907+097\*            | 1.8               | ...                    | 30      |         |
|                 |                | IGR J19140–0951         | 1.7               | 0.64                   | 29      |         |
|                 |                | 4U 1909+07              | 1.4               | 0.4                    | 24      |         |
|                 |                | XTE J1855–026           | 2.5               | ...                    | 13      |         |
|                 |                | Ser X-1                 | 1.2               | ...                    | 11      |         |
|                 |                | IGR J18483–0311         | 2.5               | ...                    | 9       |         |
| 3…………………..| 295            | GRS 1915+105            | 37.0              | 7.7                    | 646     | \(\chi\) |
|                 |                | 4U 1909+07              | 1.6               | ...                    | 26      |         |
|                 |                | H 1907+097\*            | 1.4               | 0.43                   | 24      |         |
|                 |                | Ser X-1                 | 1.6               | ...                    | 16      |         |
|                 |                | XTE J1855–026           | 2.0               | 1.4                    | 7.4     |         |
| 4…………………..| 305            | GRS 1915+105            | 26.0              | 5.2                    | 476     | \(\chi\) |
|                 |                | Aql X-1\*               | 1.5               | 6.6                    | 152     |         |
|                 |                | H 1907+097\*            | 3.1               | ...                    | 57      |         |
|                 |                | 4U 1909+07              | 1.5               | 0.54                   | 24      |         |
|                 |                | IGR J19140–0951         | 1.3               | 0.48                   | 23      |         |
|                 |                | Ser X-1                 | 1.7               | ...                    | 18      |         |
|                 |                | SS 433                  | 0.7               | ...                    | 10      |         |
| 5…………………..| 315            | GRS 1915+105            | 22.0              | 5.5                    | 297     | \(\mu, \beta\) |
|                 |                | 4U 1909+07              | 3.0               | ...                    | 39      |         |
|                 |                | IGR J19140–0951         | 2.2               | 0.8                    | 30      |         |
|                 |                | H 1907+097              | 2.0               | 0.7                    | 26      |         |
|                 |                | Ser X-1                 | 1.5               | ...                    | 11      |         |
|                 |                | Ginga 1843+009          | 2.2               | ...                    | 12      |         |
|                 |                | XTE J1855–026           | 1.7               | ...                    | 7.6     |         |
|                 |                | Aql X-1\*               | 0.8               | 1.0                    | ...     |         |
|                 |                | GRS 1915+105            | 6.9               | 1.9                    | 38      | No JEM-X data |
|                 |                | H 1907+097              | 1.3               | ...                    | 7       |         |
|                 |                | Ser X-1                 | 2.3               | ...                    | 7       |         |
|                 |                | IGR J19140–0951         | 1.1               | ...                    | 6.1     |         |
|                 |                | 4U 1909+07              | 1.3               | ...                    | 6.1     |         |
| 7…………………..| 361            | GRS 1915+105            | 15.0              | 3.5                    | 268     | \(\phi, \theta, \delta\) |
|                 |                | H 1907+097\*            | 3.2               | ...                    | 57      |         |
|                 |                | IGR J19140–0951         | 2.4               | 0.8                    | 43      |         |
|                 |                | 4U 1909+07              | 2.1               | 0.6                    | 35      |         |
|                 |                | Ser X-1                 | 1.1               | ...                    | 11      |         |
|                 |                | SS 433                  | 0.6               | ...                    | 9.0     |         |
|                 |                | XTE J1855–026           | 1.7               | ...                    | 7.5     |         |
| 8…………………..| 367\*          | GRS 1915+105            | 22.0              | 4.7                    | 242     | \(\chi\) |
|                 |                | H 1907+097\*            | 1.3               | ...                    | 14      |         |
|                 |                | 4U 1909+07              | 1.3               | ...                    | 13      |         |
|                 |                | Ser X-1                 | 1.6               | ...                    | 10      |         |
| 9…………………..| 368\*          | GRS 1915+105            | 27.0              | 5.5                    | 420     | \(\chi\) |
|                 |                | 4U 1909+07              | 1.2               | 0.6                    | 17      |         |
|                 |                | H 1907+097\*            | 0.9               | ...                    | 13      |         |
|                 |                | SS 433                  | 0.7               | ...                    | 8.5     |         |
|                 |                | Ser X-1                 | 1.0               | ...                    | 9.0     |         |
|                 |                | XTE J1855–026           | 1.5               | ...                    | 6.1     |         |
| 10………………..| 373            | GRS 1915+105            | 12.0              | 3.1                    | 227     | \(\chi, \mu, \beta\) |
|                 |                | H 1907+097\*            | 1.3               | ...                    | 23      |         |
|                 |                | Ser X-1                 | 1.4               | ...                    | 13      |         |
|                 |                | 4U 1909+07              | 0.7               | ...                    | 13      |         |
|                 |                | SS 433                  | 0.6               | ...                    | 9.8     |         |
|                 |                | IGR J19140–0951         | 0.43              | ...                    | 7.7     |         |
their true amplitude above a noise level, we estimated the variance of the radio light curve when in the nonflare intervals. The typical rms was 3.0 mJy. The flares reached maxima (calculated from the light curve with a temporal resolution of 5 minutes) of $62/\sqrt{C6}$ mJy and $60/\sqrt{C6}$ mJy on MJDs 53,296.76 and 53,296.83 respectively. Radio flares have been seen to occur as a response to each sequence of X-ray dips and spikes in this particular class (Klein-Wolt et al. 2002).

### 3.2. Observation 2: Class λ

As can be seen in Figures 3 and 4, on one occasion an X-ray cycle was followed by a radio flare indicative of an ejection event (e.g., Mirabel et al. 1998). The shape of the flare is rather symmetric. To estimate the statistical significance of the flare, we calculated the variance of the first part of the radio light curve. From this we can calculate a typical rms of 2.3 mJy. The flare thus had an amplitude of $40/\sqrt{C6} \pm 2.3$ mJy in the 5 minute bins light curve; Fig. 4. This observation of a radio flare during a class $\lambda$ is the first ever reported. As for the other classes with cycles, e.g., class $\nu$, the dips of class $\lambda$ are known to be spectrally hard (Belloni et al. 2000). This is obvious in the SR of Figure 4. The dip, which occurred at soft X-rays, ended with a soft X-ray spike corresponding to a sudden decrease of the >13 keV emission (Fig. 4).

Interestingly, two small radio flares seem to have occurred prior to the main one around MJDs 53,324.68 and 53,324.75 (Fig. 4). They had respective amplitudes of 15.1 and 11.3 mJy. The flares were then significant at 6.5 and 4.9 $\sigma$, respectively. Deep inspection of the X-ray light curve shows that they followed short X-ray dips that occurred around MJD 53,324.66 and MJD 53,324.72 (Fig. 4). Unfortunately, during the first X-ray dip, for which the decrease of the 3–13 keV count rate is clearly visible (Fig. 4), INTEGRAL did a slew between two subsequent pointings that prevented a full coverage of this interval. We can only set a lower limit on the duration of the dip of 100 s. In the second case, the delay between the return to a high degree of variability at X-ray energies and the peak of the radio flare was 0.15 hr. Although the cycle was shorter than during the long one preceding the 40 mJy flare, a similar sequence of events can be seen here. The dip is really apparent below 13 keV and is spectrally hard, as illustrated by the SR in Figure 4. The cycle ended with a return to a high level at soft X-rays associated with a slight decrease of the hard X-ray emission. As in the previous cases the cessation of the dip manifested by a peak (although of much smaller amplitude than in the main cycle) in the SR in Figure 4.

### 3.3. Observation 4: Class $\chi$

Contrary to the previous classes, GRS 1915+105 showed a relatively steady emission at all wavelengths, although some variations, in particular near the end of the observation, are visible (Fig. 5). In the radio domain the source had a mean flux of 44.9 mJy with a typical rms of 3.0 mJy (calculated from the radio light curve with a binning of 5 minutes) from MJD 53,473.10 to MJD 54,473.24.
It then slowly increased during ~4800 s to reach a mean flux of 70.4 mJy, with a rms of 4.4 mJy from MJD 53,473.30 to 53,473.42. The mean 3–13 keV JEM-X was 115.7 ± 6.8 counts s⁻¹ from MJD 53,473.10 to 54,473.24 and 107.3 ± 6.5 counts s⁻¹ later (MJD 53,473.30–53,473.42). The mean 18–50 keV ISGRI count rate was 55.3 ± 2.8 counts s⁻¹ from MJD 53,473.10 to 54,473.24 and 58.4 ± 2.7 counts s⁻¹ after (MJD 53,473.30–53,473.42).

Near the end of the observation (MJD 53,474.4), the radio flux stopped (Fig. 5). It decreased for a short time to ~59 mJy and increased to ~110 mJy after MJD 53,472.2. Note that an inspection of the radio light curve the following days showed that the radio flux was at approximately the same level (120–130 mJy) on MJD 53,477 and had decreased to ~60 mJy on MJD 53,478. This may suggest that the radio emitter, the jet, has persisted over a long period, although it showed slight variations in its strength.

3.4. Observation 5: Class μ and β

During this observation, again on two occasions, the X-ray dips were followed by radio flares with symmetric shapes (Fig. 6).

The radio flares reached their maxima on MJDs 53,504.248 and 53,504.298, respectively, with absolute peak fluxes of 58.5 and 68.3 mJy (when using 5 minute bins to estimate them). However, unlike the two other classes, they sat on top of a nonzero radio flux. The mean radio flux prior to the two flares was 35.2 mJy with an rms of 3.4 mJy. The net amplitude of the flares above the continuum was therefore 23.3 ± 3.4 mJy and 33.1 ± 3.4 mJy, for the first and second flares respectively. The time delays between the X-ray spikes halfway through the dips (the triggers of the ejections; Mirabel et al. 1998; Chaty 1998), and the radio maxima were ~0.31 and ~0.34 hr, respectively. The presence of a relatively high radio flux prior to the ejections, when GRS 1915+105 was showing a high level of very variable X-ray emission (Fig. 6), is quite interesting. This kind of steady radio flux is usually indicative of the presence of a compact jet. However, the latter is usually seen when the source shows a steady X-ray flux dominated by hard X-ray emission, its spectrum then being indicative of a hard-intermediate state (state C of Belloni et al. 2000), similar to the one seen during Obs. 4. Klein-Wolt et al. (2002) also report the presence of radio emission during class μ observation with no oscillations of the radio flux. This could indicate that the cycles in class μ are too fast to be detected at radio wavelength. We should also note that the radio nonzero continuum seems to be the tail or exponential decay of a major flare that occurred some days before the observation, as can be seen in Figure 1. As in classes ν and λ, the cycles are also well defined above 18 keV. In particular, a dip can clearly be seen at hard X-ray energies during each cycle.

4. DISCUSSION

We have presented the results of 2 yr of simultaneous monitoring campaigns on the Galactic microquasar GRS 1915+105 made with several instruments. This has allowed us to follow the behavior of the source from radio wavelengths to hard X-ray energies. The INTEGRAL observatory, thanks to its large field of view, has allowed us to quickly monitor the behavior of sources that are in the vicinity of GRS 1915+105.

In the case of GRS 1915+105, we first classified the X-ray classes of variability of the source (Appendix), and saw that GRS 1915+105 could undergo transitions through many classes of variability on short timescales (few hundreds seconds, Appendix). We report here the following specific and direct transitions: ν → ρ (Obs. 1), μ → λ and μ → δ (Obs. 2), μ → β (Obs. 5), φ → θ → δ (Obs. 7), χ → θ (Obs. 8 and 9; Ueda et al. 2006), possibly δ(?) → μ → β (Obs. 10), and δ → μ → β (Obs. 11). We then focused more particularly on three observations showing the
occurrences of X-ray cycles followed by radio flares. In a fourth observation the source was in its steady “hard” state accompanied by the presence of a persistent radio emission.

4.1. Steady Radio and X-Ray Emission

During Obs. 4, the persistent radio emission can be safely attributed to a steady compact jet, although the lack of simultaneous coverage at other radio wavelengths prevents us from precisely estimating the radio spectral index. GRS 1915+105 is in a class \( \chi \) also known as being its “hard” state (in fact it rather corresponds to a hard-intermediate state in the recent classification of Homan & Belloni 2005), a state during which strong radio emission associated to a compact jet has been seen in the past (e.g., Fuchs et al. 2003). During this particular observation, the radio flux increased by a factor of 1.57 in a rather short time (less than an hour), while the 3–13 keV and the 18–50 keV count rates remained constant at the 1 \( \sigma \) level. The fact that the X-ray count rates do not follow the evolution of the radio flux may indicate that the jet has no influence on the X-ray emission at all. However, GRS 1915+105 is a source known to follow the radio to X-ray correlation seen in many microquasars (Corbel et al. 2003; Gallo 2006), which has been widely interpreted as evidence for an influence of the jet at X-ray energies. A way to reconcile our observation to the latter interpretation is to suppose that the X-ray count rates come from “competing” media emitting in the same energy ranges, e.g., a disk, and/or a standard corona and/or the jet. A model-dependent analysis is, however, beyond the scope of this paper.

4.2. On the Generalization of the Radio to X-Ray Connection

Focusing on the observations showing X-ray cycles, the observations of links between the X-ray cycles in class \( \nu \) and \( \beta \) confirm previous findings that such events seem to be generic in those classes (Pooley & Fender 1997; Mirabel et al. 1998; Klein-Wolt et al. 2002). The observation of radio ejection in the \( \lambda \) class of variability is, however, the first ever reported. This may suggest a generalization of the fact that small-amplitude ejections in GRS 1915+105 always occur as a response to X-ray cycles, providing the X-ray hard dip is long enough (Klein-Wolt et al. 2002). The observation by Feroci et al. (1999) of an X-ray dip not followed by a radio flare during a BeppoSAX observation may be in contradiction with this generalization.

In fact, although some obvious morphological differences exist between the different classes, in terms of SR and colors they all undergo similar evolutions (Belloni et al. [2000] and Fig. 7). The cycles always begin with a transition to a low flux below 13 keV, the X-ray dip (interval I in Fig. 7), associated with a relatively bright flux above 18 keV. The 3–13 keV/18–50 keV SR has then a value of about 1. This indicates that the dip is spectrally hard. A short spike (interval II) occurs in the 3–13 keV range (it is very short in class \( \chi \)). This spike seems to be the onset of a sudden and fast change, as the rising part is still hard (SR \( \sim \) 1), although it
smoothly evolves. After the spike, however, a fast and important decrease of the hard X-ray emission (interval III) during which the SR increases greatly indicates a much softer state is reached. In class $\nu$, for example, the $18-50$ keV count rate decreases by a factor $\sim 3$. The evolution of the soft X-ray emission is less dramatic; although it decreases as well from intervals II to III in all classes, its evolution seems to be the continuation of the slow increase seen in each case at the end of interval I (Fig. 7). Mirabel et al. (1998) and Chaty (1998) identified the spike (II) in class $\beta$ as the trigger to the ejection later seen in radio. In all three cases the delay between interval (Int.) II seen at X-ray energies and the peak of the radio flare is very similar. In class $\nu$ it is respectively $\sim 0.31$ and $\sim 0.29$ hr for the first and second flares, respectively. In class $\lambda$, it is $\sim 0.31$ hr, while in class $\beta$ it is respectively $\sim 0.31$ and $\sim 0.34$ hr for the first and second flare. This similarity may suggest that the same physical mechanism in the three classes give rise to the same phenomenon. Hence if the spike (Int. II) in class $\beta$ is indeed the trigger of the ejection, it has the same role in classes $\nu$ and $\lambda$. This model-independent approach may suggest that the ejected material is the material responsible for the hard X-ray emission prior to the ejection occurring at Int. II. A similar interpretation was given by Chaty (1998) and Rodriguez et al. (2002) in the case of class $\beta$ and $\alpha$ observations.

The lack of ejection after the X-ray dip reported by Feroci et al. (1999) can then easily be understood. In their case the dip in question is not followed by a spike, while an ejection they observed follows an X-ray spike, possibly followed by an X-ray dip (but missed due to occultation of GRS 1915+105 by the Earth). Interestingly, the approximate delay between the X-ray spike and the maximum of the radio flare in this observation (taken in 1996; Feroci et al. 1999) is $\sim 0.28$ hr, and hence very similar to what we obtain in all our cases. In addition, the X-ray dip discussed in Feroci et al. (1999) seems much softer than the remaining intervals of their observation (see Table 1 of Feroci et al. 1999), as its photon index is the softest of the sequence. Putting everything together, then, it seems that we can generalize the following: plasmoid ejections always occur as response to an X-ray sequence composed of a spectrally hard X-ray dip longer than $100$ s terminated by a short X-ray spike, the latter being the trigger of the ejection. This possible generalization is even reinforced by the observation of smaller amplitude ejections following short cycles during class $\lambda$. Although the shorter duration of the events prevented us from obtaining the same details as in the main cycles, it is obvious from Figure 4 that GRS 1915+105 undergoes similar evolution during one of the shorter dips. In particular, the dip is spectrally hard (SR $\sim 1$), while it ends with a small $3-13$ keV spike; it is also visible in the SR which decreases to about 9, and therefore marks a transition to a much softer state.

4.3. A Link between the Radio Amplitude and the Duration of the X-Ray Dip?

Looking at class $\lambda$ in more detail, we detected the presence of two small radio flares, each apparently following an X-ray dip of short duration. In order to study a possible dependence of the amplitude of the radio flare on the duration of the X-ray dip, we estimated the duration of the X-ray dips in each class. Since the dips have different shapes and the transition into the dip is quite smooth, the true starting time of the dip is quite difficult to estimate. To do so, we take as the starting point of the dip the mean time between the highest point immediately preceding the transition to the dip and the time at which the bottom of the dip is truly reached. The error here is the time difference between the highest point immediately preceding the transition to the dip and the bottom of the dip. The end time is taken as the “foot” of the X-ray spike, which renders its identification easier, given that the transition into the spike is quite sudden and rapid in all cases. The results are plotted in Figure 8. A positive correlation between the two quantities is quite obvious. The linear Spearman correlation coefficient is 0.93. The best linear fit leads to $F_{15GHz}(mJy) = 0.025t(s) + 17.2$. Note, however, that a pure linear dependence of the radio amplitude versus the duration of the X-ray dip remains
unlikely as Klein-Wolt et al. (2002) remarked that for an ejection to take place a dip with a minimum duration of ~100 s is necessary. In order to populate the region around 1000 s, we searched the literature for simultaneous radio (15 GHz) and X-ray data showing the occurrences of cycles and ejections. Some clear examples are given in Pooley & Fender (1997) and Klein-Wolt et al. (2002) for a total of eight cycles occurring around MJDs 50,381.6, 50,698.8, and 51,342.1. However, in four cycles (on MJDs 50,698.76 50,698.78, 51,342.06, and 51,342.12) the radio flares sat on top of nonzero (30–60 mJy) radio continuum, which renders the estimate of the radio amplitude very uncertain. Note that the binning of 32 s presented in Klein-Wolt et al. (2002) is also another source of uncertainty. These four cycles are not included here. The radio flares around MJD 50,381.6 (Pooley & Fender 1997) also sat on a nonzero continuum, but the latter is quite weak (~10 mJy), and therefore the amplitude of the radio flare can be estimated more accurately. Finally, the last radio flare occurs on MJD 50,698.83 just after a period of ~0 mJy level. These four additional cycles are added in Figure 8, and represented as triangles. With these new points, the general tendency remains the same. The linear Spearman correlation coefficient is 0.90, and the best linear fit leads to $f_{15\text{GHz}} = 0.022(t_s) + 20.7$.

We also searched for other possible correlations between some properties of the cycles, and the amplitude of the radio flares such as, e.g., the amplitude of the spike (with respect to the bottom of the preceding dip), the amplitude of the variations of the SR after the spike, or the time delay between the X-ray spike and the peak of the radio flare. We do not find any obvious correlations between any of these quantities. The maximum variation for the SR is seen during the main $\lambda$ cycle, while it corresponds to a rather low amplitude ejection. No correlation is found between the amplitude of the spike and the amplitude of the radio flare, either. The maximum amplitude of the spike occurs during the main cycle of class $\lambda$ observation, for a relatively low amplitude radio flare. The spike with the minimum amplitude occurs during class $\beta$ observation for a radio flare of similar amplitude to that of class $\lambda$.

The correlation of the radio amplitude with the duration of the X-ray dip brings up interesting possibilities regarding the accretion-ejection links. This may indicate, for example, that during the X-ray dip energy and matter, later used to power the ejection, are accumulated. The longer the X-ray dip, the more energy and/or matter are accumulated, and the higher the radio amplitude is. This is compatible with the fact that the ejected material is the matter responsible for the hard X-ray emission suggested by the sudden decrease of the 18–50 keV emission at the spike. In that case, a longer duration of the dip would indicate that more matter, later ejected, is accumulated during the dip.

Another possible explanation (not exclusive with the previous one) relies on the so-called magnetic floods scenario/model (Tagger et al. 2004). This model was recently proposed to account for the observed accretion-ejection and quasi-periodic variability properties during the cycles observed in a class-$\beta$ observation. In this scenario, during the X-ray dip an accretion-ejection instability (AEI; Tagger & Pellat 1999) develops (and replaces the magnetorotational instability [MRI] thought to occur during the preceding luminous soft X-ray state), because a poloidal magnetic field advected with the matter has accumulated in the inner region of the disk. If the magnetic configuration is favorable, a sudden reconnection event (producing the spike) can occur between magnetic fields of opposite polarities in the disk and in the magnetospheric structure of the black hole. This would then lead to the dissipation of the accumulated field in the inner region, leading to the ejection (of the corona), and return to the MRI (Tagger et al. 2004). This scenario had some success in explaining all observational signatures (including QPOs) seen during the particular class $\beta$ these authors dealt with. This interpretation is also compatible with the observed behavior we present here, and in particular with the possible correlation between the amplitude of the radio flare and the duration of the dip (Fig. 8). In that case, the longer the dip, the more magnetic flux can be accumulated in the inner region, and again the higher the available energetic reservoir used in energizing the ejection is. This interpretation is only tentative, however, and should not hide the fact that other models may explain these observations. However, the generalization of the X-ray cycles to radio ejections and the relation between the duration of the dip and the amplitude of the ejection bring strong constraints on any attempt to model the accretion-ejection behavior in GRS 1915+105 and other microquasars. Note that the possible correlation we found here clearly needs to be confirmed through systematic inspection of simultaneous radio and X-ray data, but also adding different frequencies (e.g., IR data).

J. R. would like to thank S. Chaty for useful discussions, C. A. Oxborrow for invaluable help with the ISGRI and JEM-X data reduction and calibration and A. Gros, A. Sauvageon, and N. Produit for help on specific aspects of the INTEGRAL software. J. R. also acknowledges E. Kuulkers, and more generally the INTEGRAL and RXTE planners for their great help in scheduling the observations. D. C. H. gratefully acknowledges a fellowship from the Finnish Academy. A. P. acknowledges the Italian Space Agency financial and programmatic support via contract ASI/INAF 1/023/05/0. The authors thank the referee for his careful reading and valuable report, which helped to greatly improve the quality of this paper.

Based on observations with INTEGRAL, an ESA mission with instruments and science data center funded by ESA member states (especially the principle investigator countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic, and Poland, and with the participation of Russia and the USA. This research has made use of data obtained through the High Energy Astrophysics Science Archive Center Online Service, provided by the NASA/Goddard Space Flight Center.

APPENDIX

IDENTIFICATION OF THE X-RAY CLASSES

In all cases the identification of states is based on the simultaneous inspection of the JEM-X light curves for the general shape, and PCA (when available) for confirmation through inspection of the CC diagrams. The different responses of JEM-X and PCA prevent direct comparison of the CCs produced with the two instruments, as they lead to completely different patterns. In some cases, especially when no simultaneous coverage by RXTE is available, we identify the class as the most likely based on the resemblance with the patterns identified by Belloni et al. (2000). The multwavelength light curves and CC diagrams are reported in Figures 2–6 for the four observations discussed in detail in the paper and in Figures 10–14 for the others. As can be seen, while RXTE gives an easy access to
high time resolution light curves and CC diagrams, INTEGRAL allows us to have a continuous coverage of the source and thus study the evolution of classes while witnessing transitions between some of them.

Obs. 1 (Fig. 2) shows alternating X-ray dips and spikes (cycles), followed by intervals of a high level of X-ray flux at all energies, and variability of different durations. Deep inspection of these behaviors shows that the source was in an alternation of class $\nu$ and class $\rho$ heartbeat, as illustrated in Figure 2. As mentioned by Belloni et al. (2000), each $\nu$-type cycle is separated by the preceding one by an interval of $\rho$-type behavior. This is illustrated by the fact that the CC diagram (Fig. 2) of class $\nu$ shows the same pattern as the one from class $\rho$ with an extension toward higher values of HR2, corresponding to the dips. The radio light curve shows that at least after two sequences of X-ray dip/spike (hereafter cycles) radio flares occurred. In the past, similar radio flares have been seen to occur after each cycle (e.g., Klein-Wolt et al. 2002). This observation is one of the four whose deep analysis is presented in the core of this paper.

Obs. 2 (Fig. 3) shows a high level of very variable X-ray emission. On some occasions, one can see short dips in the soft X-ray light curves, each followed by a spike. A very variable behavior is also seen at hard X-ray energies, with occurrences of short dip clearly visible in the 18–50 keV light curve (Fig. 3). Looking more carefully at the source light curves, one can see that GRS 1915+105 seems to transit between different classes, as illustrated by the RXTE intervals (Fig. 3). Inspection of the CC diagrams shows that it started in class $\mu$, transited to a class $\lambda$, transited back to $\mu$, and evolved to a class $\gamma$. The presence of short $\sim 100$ s long X-ray dips visible in the INTEGRAL JEM-X light curves indicates that the source transits continuously from $\mu$ to $\lambda$. Deep analysis of this observation is presented in the core of this paper.

In Obs. 3 (Fig. 9) GRS 1915+105 was in a low-luminosity steady state. The 3–13 keV JEM-X count rate was around 110 counts s$^{-1}$, while the 18–50 keV count rate was around 80 counts s$^{-1}$, with a slight decrease to about 70 counts s$^{-1}$ near the end of the observation. The 2–18 keV PCA count rate was around 1800 counts s$^{-1}$. All light curves show a high degree of rapid variability. Both the light curve and the CC diagrams indicate the source was in class $\chi$. No RTs were performed during this interval. The values of HR1 and HR2 are indicative of a very hard class $\chi$ (Fig. 9). In particular, the source is much harder here than during Obs. 4, although both observations belong to the same class.

Obs. 4 (Fig. 5) is very similar to Obs. 3, although GRS 1915+105 was slightly fainter at hard X-ray energies and showed lower values of the HRs. Near MJD 53,474.1 the source fluxes increased suddenly. This indicates that it underwent a transition to a brighter class, confirmed by the variations of the ASM light curve (Fig. 1). Simultaneous coverage at radio wavelengths shows a rather steady flux at around 50 mJy, although some variations are visible. In particular, the radio flux increased up to 100 mJy near the end of the observation (Fig. 5). The global X-ray behavior indicates that GRS 1915+105 was in a radio-loud class $\chi$. This observation is one of the four that is deeply analyzed in this paper.
Obs. 5 (Fig. 6) shows that GRS 1915+105 was in classes of high X-ray flux with a high degree of variability. It is interesting to note that the overall 18–50 keV variability increased during the observation. Although the mean 18–50 keV flux remained quite bright around 40–50 counts s$^{-1}$, significant dips and spikes can be seen, some in simultaneity with those seen at soft X-rays. It is clear from Figure 6 that it transited at least between two such classes. Inspection of the CC diagrams shows that it started in a class C2 and finished in a class C1. Our radio observation shows a roughly constant flux of $\sim$40 mJy up to MJD 53,504.35, where two radio flares occurred after occurrences of dip-spike cycles in the X-ray domain. This observation is one of the four that are deeply analyzed in this paper.

Obs. 6 was of poor quality due to the effects of high solar activity and was therefore not considered in this analysis.

Obs. 7 (Fig. 10) shows a clear transition from a class with a very low level of X-ray emission to a class of high flux with high variability with similar evolving patterns at both soft and hard X-rays. The change from the first class to the last seems to occur through a third one, as illustrated by the differences in the JEM-X and ISGRI light curves, but the lack of RXTE data during this interval prevents us from obtaining any clear identification. A zoom on the intermediate part (Fig. 11) shows occurrences of 3–13 keV “M-shaped” patterns typical of class C3. In the mean time, the 18–50 keV light curve shows similar variability (the M can be seen in coincidence with those occurring at soft X-rays) and a high variability. The SR indicates the source was hard during the dips of the M, which is in agreement with the known behavior of class C3 (Belloni et al. 2000). This class shows a behavior very similar to other classes with cycles, i.e., spectrally hard dips ended by a soft X-ray spike marking the disappearance of the hard X-ray emission (and transition to a soft state as illustrated by the variations of the SR visible in Fig. 11). The level of radio emission was quite low, with some variability, which is also in agreement with GRS 1915+105 being in class C3 (Klein-Wolt et al. 2002). This may further corroborates the generalization of the X-ray to radio connection presented in this paper, although the resolution at radio wavelength do not allow us to identify any radio flares.

The analysis of the RXTE data of the beginning and end of the INTEGRAL observations (Fig. 10) indicates that GRS 1915+105 started in class C3 and ended in class C7.

Obs. 8 and 9 (Fig. 12) were part of a large multiwavelength campaign involving the Suzaku satellite at high energy. The INTEGRAL light curves are first very similar to the light curves of Obs. 4, which was indeed a class C3. The higher level of soft X-ray emission, and slightly lower level of hard X-ray emission tend to indicate a rather soft class C$'$. In the second part, a flare occurred at the beginning of the
observing interval at both soft and hard X-rays. GRS 1915+105 then returned to a rather steady emission before transiting to a class that showed similar patterns at soft and hard X-rays. The lack of simultaneous RXTE coverage prevents us from securely identifying the class of variability. A zoom on the JEM-X light curve (Fig. 12) does not show any easily identifiable pattern. Furthermore, the 3–13 keV/18–50 keV SR has a value quite similar to that of Obs. 8 (Fig. 12) and even to Obs. 4 (not shown). Therefore, it seems the source was still in a class/C31. Ueda et al. (2006) presented preliminary results of the whole campaign; they, in particular, showed that GRS 1915+105 started in a class/C31 showing the presence of a 6 Hz QPO, and transited in a class/θ. The class/θ, however, occurred between both INTEGRAL intervals. The mean level of radio emission was 31 mJy until MJD 53,660.7 and then increased to about 39 mJy during the first radio interval (Fig. 12). The mean level of radio emission during the second interval was about 40 mJy. The shape of the radio light curve may suggest that ejection had taken place between the two observing intervals. A simultaneous Very Large Array (VLA) light curve (Ueda et al. 2006) is also compatible with this interpretation. Ueda et al. (2006) suggested that ejection of material was triggered at the transition from spectral state C to spectral state A (hard intermediate to soft state), similar to our interpretation.

Obs. 10 (Fig. 13), shows a complex behavior made of several possible transitions. The radio light curve (Fig. 13) also indicates two different behaviors. In the first part (MJD 53,676.56–53,676.99), the mean 15 GHz flux was $\sim$40.4 mJy with an rms of 10.4 mJy. In the second part (MJD 53,676.77–53,676.841), the mean flux was 36.5 mJy, and the variability of the radio emission had increased significantly with an rms of 19.6 mJy. This increase seems to be correlated to the X-ray behavior. Around MJD 51,678.9 a dip at soft X-ray energies associated to a 6 Hz QPO, and transited in a class/θ. The class/θ, however, occurred between both INTEGRAL intervals. The mean level of radio emission was 31 mJy until MJD 53,660.7 and then increased to about 39 mJy during the first radio interval (Fig. 12). The mean level of radio emission during the second interval was about 40 mJy. The shape of the radio light curve may suggest that ejection had taken place between the two observing intervals. A simultaneous Very Large Array (VLA) light curve (Ueda et al. 2006) is also compatible with this interpretation. Ueda et al. (2006) suggested that ejection of material was triggered at the transition from spectral state C to spectral state A (hard intermediate to soft state), similar to our interpretation.

Obs. 11 (Fig. 14) shows a complex behavior made of several possible transitions. The radio light curve (Fig. 14) also indicates two different behaviors. In the first part (MJD 53,676.56–53,676.99), the mean 15 GHz flux was $\sim$40.4 mJy with an rms of 10.4 mJy. In the second part (MJD 53,676.77–53,676.841), the mean flux was 36.5 mJy, and the variability of the radio emission had increased significantly with an rms of 19.6 mJy. This increase seems to be correlated to the X-ray behavior. Around MJD 51,678.9 a dip at soft X-ray energies associated to a 6 Hz QPO, and transited in a class/θ. The class/θ, however, occurred between both INTEGRAL intervals. The mean level of radio emission was 31 mJy until MJD 53,660.7 and then increased to about 39 mJy during the first radio interval (Fig. 12). The mean level of radio emission during the second interval was about 40 mJy. The shape of the radio light curve may suggest that ejection had taken place between the two observing intervals. A simultaneous Very Large Array (VLA) light curve (Ueda et al. 2006) is also compatible with this interpretation. Ueda et al. (2006) suggested that ejection of material was triggered at the transition from spectral state C to spectral state A (hard intermediate to soft state), similar to our interpretation.
Obs. 11 (Fig. 14) also shows several transitions. We do not have any radio coverage during this observation. Although our RXTE observations arrive late in the INTEGRAL coverage (Fig. 14), it seems that during the first part of the observation (up to about MJD 53,695), GRS 1915+105 was in the same type of variability. Zooms on the JEM-X and ISGRI light curves during this first part (not shown) indeed indicate similar morphologies. Inspection of the CC diagram of the first sample of the RXTE light curve shows the source was in a class δ (Fig. 14, right). The following samples show that GRS 1915+105 had changed class. This is especially indicated by the track in the CC diagram that shows an incursion in the low HR1 region, with an HR2 as high as 0.05. This pattern and the shape of the light curve is what is observed during class μ. However, typical class μ, such as the one observed during Obs. 3, show a longer extension toward higher value of HR1 (Fig. 3, right). This may simply indicate that while in the first hundred seconds of the interval the variations were still similar to δ, GRS 1915+105 evolved toward class γ (Fig. 14, right). The behavior was the same at soft and hard X-rays with occurrences of long dips in both light curves. This is reminiscent of what we saw during Obs. 5 (Fig. 6) with the occurrence of γ-like cycles after some times (Fig. 14, right).

REFERENCES

Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99
Belloni, T., Klein-Wolt, M., Méndez, M., van der Klis, M., & van Paradijs, J. 2000, A&A, 355, 271
Belloni, T., Méndez, M., King, A. R., van der Klis, M., & van Paradijs, J. 1997, ApJ, 488, L109
Chapuis, C., & Corbel, S. 2004, A&A, 414, 659
Chaty, S. 1998, Ph.D. thesis, Univ. Paris 7
Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007
Dhawan, V., Mirabel, I. F., & Rodríguez, L. F. 2000, ApJ, 543, 373
Eikenberry, S. S., Matthews, K., Morgan, E. H., Remillard, R. A., & Nelson, R. W. 1998, ApJ, 494, L61
Fender, R. P., & Belloni, T. 2004, ARA&A, 42, 317
Fender, R. P., Garrington, S. T., McKay, D. J., Muxlow, T. W. B., Pooley, G. G., Spencer, R. E., Stirling, A. M., & Waltman, E. B. 1999, MNRAS, 304, 865
Fender, R., & Pooley, G. 1998, MNRAS, 300, 573
Feroci, M., Matt, G., Pooley, G., Costa, E., Tavani, M., & Belloni, T. 1999, A&A, 351, 985
Fuchs, Y., et al. 2003, A&A, 409, L35
Fritz, S., Kreykenbohm, I., Wilms, J., Staubert, R., Bayazit, F., Pottschmidt, K., Rodriguez, J., & Santangelo, A. 2006, A&A, 458, 885
Gallo, E. 2006, in Proc. VI Microquasar Workshop: Microquasars and Beyond, ed. T. Belloni (Como: Proc. Science), 9.1
Goldwurm, A., et al. 2003, A&A, 411, L223
Harlaftis, E. T., & Greiner, J. 2004, A&A, 414, L13
Homan, J., & Belloni, T. 2005, Ap&SS, 300, 107
Klein-Wolt, M., Fender, R. P., Pooley, G. G., Belloni, T., Migliari, S., Morgan, E. H., & van der Klis, M. 2002, MNRAS, 331, 745
Lebrun, F., et al. 2003, A&A, 411, L141
Lund, N., et al. 2003, A&A, 411, L231
Mirabel, I. F., Dhawan, V., Chaty, S., Rodriguez, L. F., Marti, J., Robinson, C. R., Swank, J., & Geballe, T. 1998, A&A, 330, L9
Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46
———. 1998, Nature, 392, 673
Morgan, E. H., Remillard, R. A., & Greiner, J. 1997, ApJ, 482, 993
Pooley, G. G., & Fender, R. P. 1997, MNRAS, 292, 925
Rodriguez, J., Cabanas, C., Hannikainen, D. C., Beckmann, V., Shaw, S. E., & Schultz, J. 2005, A&A, 432, 235
Rodriguez, J., Durouchoux, Ph., Mirabel, I. F., Ueda, Y., Tagger, M., & Yamaoka, K. 2002, A&A, 386, 271
Rodriguez, J., & Shaw, S. E. 2005, Astron. Tel., 660
Rodriguez, J., Shaw, S. E., & Corbel, S. 2006, A&A, 451, 1045
Rodriguez, J., et al. 2008, ApJ, 675, 1449
Tagger, M., & Pellat, R. 1999, A&A, 349, 1003
Tagger, M., Varnière, P., Rodriguez, J., & Pellat, R. 2004, ApJ, 607, 410
Ueda, Y., et al. 2006, in Proc. VI Microquasar Workshop: Microquasars and Beyond, ed. T. Belloni (Como: Proc. Science), 23.1
Vadawale, S. V., Rao, A. R., Naik, S., Yadav, J. S., Ishwara-Chandra, C. H., Pramesh Rao, A., & Pooley, G. G. 2003, ApJ, 597, 1023