1. INTRODUCTION

Large superluminal outflows/jets that appear to move faster than light are widely studied in active galactic nuclei (AGNs) and quasars yet remain poorly understood. (The first AGN was discovered by Carl Seyfert in 1943!) This is due to the long timescales associated with these systems, as well as the fact that the central part of these systems is usually obscured by large amounts of dust. Microquasars in our Galaxy are stellar-mass analogs of the massive black hole systems in quasars and AGNs. Microquasars are closer, smaller, and show faster variability that is easily observable. Mirabel & Rodríguez (1994) discovered the first microquasar, GRS 1915+105, in our Galaxy with superluminal jets. The black hole mass in GRS 1915+105 is determined to be $14 \pm 4 \, M_\odot$ (Greiner et al. 2001). This microquasar shows exceptionally high variability in both X-rays and radio. Since 1996, rich X-ray variability of this source has been observed by the Rossi $X$-Ray Timing Explorer ($RXTE$; Morgan et al. 1997; Muno et al. 1999) and by the Indian X-Ray Astronomy Experiment, IXAE, on board the Indian satellite IRS-P3 (Yadav et al. 1999). Belloni et al. (2000) have classified the complex X-ray variability of GRS 1915+105 in 12 separate classes on the basis of their light curves and the color–color diagrams and suggested three basic states of this source, namely, low hard state, high soft state, and low soft state.

The radio emission from GRS 1915+105 can be broadly classified into three types: (1) steady radio jets (radio plateau state), (2) oscillations/baby jets (discrete jets) of 20–40 minutes duration in infrared (IR) and radio, and (3) large superluminal radio jets. The steady radio jets of 20–160 mJy flux density are associated with the canonical low hard X-ray state and observed for extended durations (Muno et al. 2001; Fuchs et al. 2003b). These are optically thick compact jets of <200 AU with velocity $\beta$ of 0.1–0.4 (Dhawan et al. 2000; Ribó et al. 2004). The radio emission is correlated with the X-ray emission as $L_{\text{radio}} \propto L_X^{0.8}$ for several different sources (Gallo et al. 2003). Pooley & Fender (1997) observed radio oscillations with delayed emission at lower frequency. Simultaneous X-ray, IR, and radio multiwavelength observations provided the first major step in our understanding of disk-jet interaction and suggested that the spike in X-rays coincides with the beginning of an IR flare, and it has self-absorbed synchrotron emission associated with adiabatic expansion (Eikenberry et al. 1998; Mirabel et al. 1998). These are also compact jets with velocity $\beta \sim 1$ (Dhawan et al. 2000). It is further suggested that the spike in X-rays is associated with the change of the X-ray state due to a major ejection episode (Yadav 2001). This is consistent with the suggestion that it is the coronal material and not the disk material (or any other accretion flow associated with the low hard state) that is ejected prior to radio flares (Rau & Greiner 2003; Vadawale et al. 2003; Fender et al. 2004; Rothstein et al. 2005).

The relativistic superluminal jets with up to 1 Jy flux density have steep radio spectra and are observed at large distances, a few hundred to 5000 AU, from the core (Mirabel & Rodríguez 1994; Fender et al. 1999; Dhawan et al. 2000). These radio jets are very energetic, with luminosity close to the Eddington luminosity, $L_{\text{Edd}}$, and have been observed in several sources (Fender et al. 1999; Hjellming & Rupen 1995; Wu et al. 2002; Orosz et al. 2001). Progress in our understanding of these jets, especially their connection to the accretion disk, has been slow. A semiquantitative model is proposed for the disk-jet coupling (Fender et al. 2004; Fender & Belloni 2004) that puts all available observational details into perspective, but the scope to gain new insight or new information about disk-jet interaction seems limited (Remillard 2005). The physical connection between X-ray emission and the superluminal flares has been the hardest to understand. However, a general trend is emerging that the plateau states are generally followed (and perhaps preceded) by superluminal flares (Fender & Belloni 2004).

In this paper, we investigate the association of large superluminal jets with the radio plateau. We have analyzed the available $RXTE$ Proportional Counter Array (PCA) and High-Energy X-Ray Timing Experiment (HEXTE) X-ray data during radio plateaux and the radio flare data from the Green Bank Interferometer (GBI). We describe our selection criterion and discuss in detail the morphology of superluminal radio flares. We present tight correlations between parameters of the accretion disk and the superluminal jets. We suggest that the accretion disk during radio plateaux is always associated with radiation-driven wind and corotate...
our suggestion with supporting evidence. Finally, we provide a simple model for the origin of superluminal jets and discuss its implications for Galactic and extragalactic radio jet sources.

2. OBSERVATIONS AND ANALYSIS

All the radio flares observed in GRS 1915+105 can be broadly put into two groups on the basis of their flux, radio spectrum, and spatial distribution: (1) the superluminal flares (200–1000 mJy), which have steep radio spectra and are seen at large distances (>240 AU), and (2) all other flares (5–360 mJy), which include the preplateau flares, radio oscillations and discrete flares, and the steady radio flares during the plateaux. All these flares have flat radio spectra and are observed close to the compact object (<200 AU).

It is the superluminal flares that are hard to understand. The other flares in the latter group are studied in detail and understood fairly well (this is discussed in § 4). In the internal shock model for superluminal radio jets in microquasars, an exponential decay is suggested once the shock is fully developed (Kaiser et al. 2000).

It is also found that the radio plateau is always associated with a superluminal radio flare (Fender et al. 1999; Klein-Wolt et al. 2002; Vadawale et al. 2003). We searched 2.25 GHz GBI radio monitoring data during the period from 1996 December to 2000 April and selected radio plateaux and the following radio flares, which decay exponentially. The preplateau radio flares do not follow exponential decay and are like the oscillations and discrete flares but closely spaced in time as described in the next paragraph. Seven flares are found to satisfy our criteria for superluminal flares and are listed in Table 1. One more radio flare on 2001 July 16 that was observed by the Very Large Baseline Array (VLBA) and Ratan 315 radio telescope is also added in Table 1. VLBA observations clearly showed an ejecta well separated from the core (Dhawan et al. 2003). This plus two more flares of eight flares listed in Table 1 show moving ejecta well separated from the core (Fender et al. 1999; Dhawan et al. 2000).

In Table 1, the rise time is the total time taken by a radio flare to rise from the plateau flux to the peak flux. The gaps in the GBI data put an upper limit on the rise time (<1 day). For the 340 mJy flare on 1999 January 30 the rise time is 0.25 days, while for the 710 mJy flare on 1998 June 3 the rise time is 0.3 days.

These values are consistent with the reported values of 0.25–0.5 days for different microquasars (Fender et al. 2004). The decay time constant is calculated by fitting an exponential decay profile to the radio flare data. The contribution due to the continuous radio plateau (such as in the flares on 1998 April 13 and 30) or any other minor flare if any is removed prior to profile fitting. The decay time constant varies from 1.12 to 4.02 days. The superluminal radio flare profile can be described as fast rise and exponential decay (FRED). Here fast rise (0.2–0.5 days) is in comparison to the decay time.

For comparison the oscillations/discrete radio jets have rise and decay time in the range of 0.1–0.3 hr (Mirabel et al. 1998; Ishwara-Chandra et al. 2002). The integrated radio flux is calculated by integrating the fitted exponential function over a duration of 3 times the decay time constant.

The typical sequence of events for a superluminal radio flare is shown in Figure 1 for the 550 mJy radio flare on 1997 October 30 (gap in GBI data at peak) and for the 340 mJy radio flare on 1999 January 30. The start of the radio flares is offset to zero. A superluminal event starts with small preplateau flares followed by a steady long plateau, followed by superluminal radio flares. We have described the radio plateau state and the superluminal flares in § 1. The preplateau flares are studied in detail using the Giant Metrewave Radio Telescope (GMRT) and the Ryle Radio Telescope data for the 2001 July 16 superluminal flare (Ishwara-Chandra et al. 2002; Yadav et al. 2002). These are discrete ejections of adiabatically expanding synchrotron clouds with flat radio emission (delayed emission at lower frequency). They are like the oscillations/discrete but closely spaced in time and hence produce overlapping radio flares. Radio emission at 1.4 and 15 GHz supports a flat radio spectrum.

We study X-ray properties during radio plateaux within the preceding week from the start of the superluminal flares to avoid changes in the accretion disk over the long durations of plateaux (from −7 to −2 in Fig. 1). We also avoid the last day of the plateaux as radio data suggest rapid changes in the accretion disk.

For the timing analysis, we used single-bit-mode RXTE PCA data in the energy ranges 3.6–5.7 and 5.7–14.8 keV. Power density spectra of 256 bin light curves are generated and co-added for every 16 s. The power density spectra are normalized. We fit a power-law + Lorentzian model and have calculated the quasiperiodic oscillation (QPO) frequency. We show in Figure 2 the power density spectra (PDSs) in the 0.09–9 Hz frequency range observed on 1998 April 28 and 2001 July 11. Strong QPOs are seen at 1.4 and 2.4 Hz in the PDSs observed on 1998 April 28 and 2001 July 11, respectively. The first harmonics are also visible in the spectra. For spectral analysis, we used PCA standard-2 data (3–35 keV) and cluster 0 data from HEXTE (20–150 keV).

We added a 0.5% systematic error in PCA data. Standard procedures for data reduction, response matrix, and background estimation are followed using HEASOFT (ver. 5.2). Muno et al. (1999) have shown that a spectral fit using the sum of a multicolor disk-blackbody power, a power law, and a Gaussian line during plateaux results in high values of the inner disk temperature (≥3 keV) and an unrealistic accretion disk radius (≤2 km). Fuchs et al. (2003b) also drew a similar conclusion while analyzing X-ray properties during a plateau state using International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and RXTE data. Rau & Greiner (2003) analyzed a large sample of RXTE observations belonging to radio plateaux using the multicolor disk-blackbody + power-law spectrum reflected from the accretion disk. This model adequately describes the X-ray spectra of all the observations, but it yields extremely high values of the reflection parameter that are inconsistent with other measurements.

A spectral model of a simple power law with a multicolor disk-blackbody and a Gaussian provides reasonable values of the temperature and inner radius of the disk if the energy spectrum is disk dominated as is the case during class β (Migliari & Belloni 2003). During the plateaux, the source is in the very high luminosity state (VHS) with power index Γ > 2. The spectrum is dominated by the Compton scattered emission (>85%) rather than the disk. The Comptonized emission has a complex spectrum shape showing features from both thermal and nonthermal electrons (Done & Kubota 2006). It suggests the presence of an optically thick inner disk corona that drains energy from the disk and reduces the disk temperature. The presence of QPOs in the 1.4–2.6 Hz frequency range is consistent with the large corona (see Table 1). This will require an additional component in the spectral model during the plateaux. A three-component model (multicolor disk-blackbody + power law + a Comptonized component (CompTT)) with a Gaussian line at 6.4 keV is reported to provide more realistic values of the inner disk temperature and the disk radius (Rao et al. 2000a; Vadawale et al. 2003). We have used this model for our X-ray spectral analysis during the plateaux listed in Table 1.

The absorption column density, $N_{\text{H}}$, is kept as a free parameter. The integrated X-ray flux for the energy range 3–150 keV and the derived values of $N_{\text{H}}$ are listed in Table 1. The other best-fit X-ray spectral parameters are given in Table 2 along with the flux of the individual spectral components. The $\chi^2$ of our spectral fits falls...
| MJD       | Date         | Peak Flux (mJy) | Rise Time (days) | Decay Time Constant (days) | Radio Flux \( (\text{Jy days}) \) | GBI Flux (mJy) | ASM Flux (counts s\(^{-1}\)) | Date of RXTE Obs. | QPO Freq. (Hz) | Total X-Ray Flux\(^b\) | \( N_H \) (10\(^{22}\) cm\(^{-2}\)) |
|-----------|--------------|-----------------|------------------|---------------------------|---------------------------------|----------------|-----------------------------|------------------|----------------|------------------|-----------------------------|
| 50,750... | 1997 Oct 30  | 550             | <0.6             | 3.16±0.07                 | 2.20\(^*\)                      | 47.3           | 35.9                        | 1997 Oct 25      | 1.88           | 2.04             | 13.27±0.06                  |
| 50,916... | 1998 Apr 13  | 920             | <0.8             | 4.02±0.33                 | 3.04                           | 91.0           | 48.2                        | 1998 Apr 11      | 1.60           | 2.42             | 14.95±0.02                  |
| 50,933... | 1998 Apr 30  | 580             | <0.9             | 3.98±0.13                 | 3.02                           | 91.0           | 44.9                        | 1998 Apr 28      | 1.41           | 2.34             | 13.55±0.01                  |
| 50,967... | 1998 Jun 3   | 710             | 0.3              | 2.82±0.18                 | 2.15                           | 56.2           | 36.5                        | 1998 May 31      | 1.76           | 2.14             | 12.99±0.12                  |
| 51,204... | 1999 Jan 30  | 340             | 0.25             | 1.12±0.03                 | 0.36                           | 27.8           | 33.8                        | 1999 Jan 24      | 2.55           | 1.84             | 11.19±0.02                  |
| 51,337... | 1999 Jun 8   | 400             | <0.7             | 2.67±0.12                 | 1.58                           | 45.5           | 35.2                        | 1999 Jun 3       | 1.77           | 1.98             | 12.43±0.05                  |
| 51,535... | 1999 Dec 23  | 510             | <0.8             | 2.67±0.12                 | 1.75\(^*\)                     | 51.3           | 38.9                        | 1999 Dec 21      | 2.12           | 2.23             | 13.61±1.17                  |
| 52,105... | 2001 Jul 16  | 210             | <0.7             | 1.77±0.20                 | 0.62\(^*\)                     | 20.0           | 30.0                        | 2001 Jul 11      | 2.40           | 1.75             | 10.60±0.77                  |

**Notes.**—The X-ray properties are from RXTE PCA/HEXTE data during the preceding radio plateau. See the text for details.

\(^a\) The integrated flux is obtained by fitting an exponential function to the flare profile and integrating the function over a duration of 3 times the decay time constant. Typical errors are ±0.05; the errors are larger (0.15–3.0) for values marked an asterisk due to a large gap in the GBI radio data or due to contribution by an additional radio flare.

\(^b\) Integrated 3–150 keV X-ray flux in 10\(^{-8}\) ergs cm\(^{-2}\) s\(^{-1}\).

\(^c\) VLBA radio data (see text for details).
Fig. 1.— Top: GBI 2.25 GHz radio data for 1999 January 30 (start at MJD 51,204.7) and 1997 October 30 (start at MJD 50,750.6) large superluminal radio flares. The start of the flares is offset to 0. It includes preplateau flares, the plateau state, and the large superluminal radio flare. The dotted line connects the data points of the 1999 January 30 superluminal radio flare to guide the eyes. Bottom: Radio spectral index is shown in the bottom panel.

Fig. 2.— Normalized power density spectra in the 0.09–9 Hz frequency range observed on 1998 April 28 and 2001 July 11. Strong QPOs are seen at 1.4 and 2.4 Hz in the PDSs observed on 1998 April 28 and 2001 July 11, respectively. The first harmonics are also visible in spectra.
in the range 0.81–1.4 (for 74–94 dof [degrees of freedom]). The spectrum is dominated by the Compton scattering emission, and the contribution from the disk is limited to less than 13%.

3. RESULTS AND DISCUSSION

It is widely believed that the coronal material (not the disk material) is ejected prior to the radio flares as discussed above. It is consistent with the fact that radio flares are observed during the transition from the low hard state to the high soft state but never observed during the opposite transition (Klein-Wolt et al. 2002). All the radio flares observed close to the core in GRS 1915+105 can be further subdivided into two groups of the associated change observed in the accretion disk: (1) the persistent radio flares during the plateaux with a steady accretion disk (no change associated with radio flares) and (2) all other radio flares, which accompany clear changes in the accretion disk. In the former case, inflow and outflow in the accretion disk are in equilibrium. Both the accretion disk and the radio flare are in a steady state, and radio emission is tightly correlated with the X-ray luminosity as discussed above. In the latter case, the hard X-ray component (Compton component) is either partly or completely affected. The large changes will result in a state transition (Rothstein et al. 2005; Rau & Greiner 2003; Yadav 2001). The accretion disk may come back to its initial state after some time or may remain in the new state for a longer duration. If the accretion disk is in some periodic state like such as class β or θ (Belloni et al. 2000), it produces IR and radio oscillations. Eikenberry et al. (1998) suggested that the spike in X-rays during class β is related to mass ejection and the ejected matter decouples from the accretion disk. It is further shown that the intensity of these IR and radio jets increases with the X-ray hard ratio during the low hard state preceding the spike (Yadav 2001). For these oscillations and the preplateau radio flares, all the available experimental data of the time delay in the emission at lower frequencies can be adequately explained using an adiabatically expanding synchrotron-emitting cloud ejected from the accretion disk (Ishwara-Chandra et al. 2002). These results suggest that the ejected matter behaves like an adiabatically expanding synchrotron cloud that has been decoupled from the accretion disk.

Muno et al. (2001) have shown that radio emission during large superluminal flares is decoupled from the accretion disk. This view is further strengthened by the fact that superluminal flares appear at distances of few hundred AU from the core (Fender et al. 1999; Dhawan et al. 2000). Fender et al. (1999) have observed superluminal flares after a radio plateau state. To investigate the association of superluminal flares with plateaux, we plot in Figure 3 the total 3–150 keV X-ray flux during the preceding plateau versus the integrated radio flux of the superluminal flare. We derive a correlation coefficient of 0.99, suggesting a strong connection between the total X-ray flux during the preceding plateau state and the integrated radio flux of the superluminal flare. We also find a strong correlation between the All-Sky Monitor (ASM) count rate and the plateau radio flux and between the ASM count rate and the integrated radio flux as discussed by Vadawale et al. (2003; not shown here). In Figure 4, we plot the QPO frequency from our timing analysis of the X-ray data during the plateau state as a function of the decay time constant of the following superluminal radio flare. It again shows a tight correlation with a correlation coefficient of 0.98. The remarkable feature of our findings here is that the parameters calculated using completely independent spectral and timing analyses bring out a clear connection between the accretion disk during the plateau state and the following superluminal radio flare.

In the last column of Table 1, we give the calculated value of $N_{\text{H}}$, which ranges from $10^{20}$ to $15 \times 10^{22}$ cm$^{-2}$. These values are higher than those commonly used, $N_{\text{H}} \sim (5–6) \times 10^{22}$ cm$^{-2}$, for spectral analysis of GRS 1915+105 by several authors (Belloni et al. 1997; Muno et al. 1999; Yadav 2001; Rau & Greiner 2003). Radio emission from atomic hydrogen and molecular hydrogen together gives a line-of-sight column density $\geq 3 \times 10^{22}$ cm$^{-2}$ (Dickey & Lockman 1990; Dame et al. 2001). Belloni et al. (2000) found for the first time evidence for a variable $N_{\text{H}}$ during the
plateaux (class $\chi_1$ and $\chi_3$) and suggested the presence of a large intrinsic absorber. The value of $N_H$ is estimated to be 6 × 10$^{22}$ cm$^{-2}$ for the plateau state, while for the nonplateau low hard state, it is found to be 2 × 10$^{22}$ cm$^{-2}$.

Lee et al. (2002) have analyzed Chandra and RXTE X-ray data during a radio plateau state with GBI radio flux of 20 mJy at 2.25 GHz on 2000 April 24. The total 2–25 keV X-ray flux is 1.89 × 10$^{-8}$ ergs cm$^{-2}$ s$^{-1}$. These plateau conditions are identical (in radio and X-ray flux) to that preceding the superluminal flare on 2001 July 16 listed in Table 1. The $K$-absorption edges from Fe, Si, and others are detected in Chandra data, which suggests the presence of a warm absorber in the vicinity of the accretion disk. The $N_H$ derived from the Fe absorption edge is found to be 9.3 × 10$^{22}$ cm$^{-2}$ for solar abundances, which is in agreement with our calculated value of $N_H \sim 10.6^{+0.8}_{-0.4} \times 10^{22}$ cm$^{-2}$ for the superluminal flare on 2001 July 16 (see Fig. 5). The lower limit of the bolometric luminosity is $L_{bol} \sim L_X = 6.4 \times 10^{38}$ ergs s$^{-1}$, which is 0.35 times the Eddington luminosity, $L_{edd}$, for a black hole of mass 14 $M_\odot$ (Lee et al. 2002). The corresponding lower limit of the bolometric luminosity for the X-ray flux listed in Table 1 falls in the range of (0.35–0.48)L$_{edd}$. Lee et al. (2002) have suggested wind from the accretion disk as the source of the observed enhanced $N_H$. One can define the wind (spherical) mass outflow rate as $m_{wind} \sim 4 \pi r^2 \rho c (\Omega/4\pi) \sim 9.5 \times 10^{10} (\Omega/4\pi) g$ s$^{-1}$, where $r$ is the radius (10$^{11}$ cm), $\rho$ is the density of the absorbing material, and $c$ is the wind velocity (100 km s$^{-1}$). The accretion rate is $m_{accr} = L_{bol}/(\eta c^2) \geq L_X/(\eta c^2) \sim 7.1 \times 10^{18}$ g s$^{-1}$, where the efficiency $\eta \sim 0.1$. It shows that as the covering fraction $(\Omega/4\pi)$ approaches unity, the wind outflow rate, $m_{wind}$, is comparable to $m_{accr}$. During the low hard state, the efficiency of compact persistent radio jets is estimated to be ~5% (Fender 2001; Fender et al. 2004). In this case, losses due to nonradiative process (such as adiabatic expansion) are likely to dominate. Our estimate of $m_{wind}$ above suggests that the major part of the accretion energy goes to the wind during the plateaux. When GRS 1915+105 is accreting near $L_{edd}$, the presence of a radiation-driven wind is always expected, and the wind density should be a strong function of the disk luminosity. Our derived values of $N_H$ show strong dependence on observed total X-ray flux with a correlation coefficient of 0.995, which is shown in Figure 5. The dotted line is a linear fit to our data (plus signs with error bars). The open circle with error bars shows the value derived from Chandra and RXTE data as discussed above, which is in agreement with our data within the error bars. Kotani et al. (2000) have estimated $N_H \sim 10^{24}$ cm$^{-2}$ from Advanced Satellite for Cosmology and Astrophysics (ASCA) data. Our estimates of $N_H$ fall between these two values.

The best-fit X-ray spectral parameters are given in Table 2 along with the flux of individual spectral components. The spectrum is dominated by the Compton scattering emission, and the contribution from the disk is limited to <13%. The inner disk temperature ($kT_{in}$) and the plasma temperature ($kT_e$) are ~0.5 and 4–7 keV, respectively, which are in an acceptable range (Wada et al. 2003). The derived inner disk radii ($R_d$) are in the physically plausible range of (10–25)$R_g$ for a 14 ± 4 $M_\odot$ black hole. As the total X-ray flux rises from 1.75 × 10$^{-8}$ to 2.42 × 10$^{-8}$ ergs cm$^{-2}$ s$^{-1}$, the major part of it (close to 80%) goes to the Compton component, which shows a strong correlation with $N_H$ (this is analogous to the solar wind originating from the dense solar corona). Our spectral model does not overestimate the value of $N_H$. Wada et al. (2003) have analyzed preplateau data of 2001 June 30, when the source was in the low hard state (nonplateau; the plateau started on 2001 July 3) and estimated $N_H \sim 1.65 \times 10^{22}$ cm$^{-2}$, which is close to the value estimated by Belloni et al. (2000) for the nonplateau low hard state. We have also studied the X-ray class $\beta$ in GRS 1915+105 using this spectral model, which results in $N_H \sim 7 \times 10^{22}$ cm$^{-2}$ for $\chi^2$ close to 1 (Yadav 2006). Similar values of $N_H$ were used earlier for spectral studies of the X-ray class $\beta$ (Migliari & Belloni 2003).

Our calculated power density spectra shown in Figure 2 also independently lend support to the presence of wind during the plateau state. In the high soft state, the PDS is a featureless power law of $dP/d\nu \propto \nu^{-\alpha}$, where $\alpha \sim 4/3$. On the other hand, the low hard state is dominated by the Compton scattering photon emission, and the PDS develops bandwidth-limited noise, a flat shoulder with a QPO at ~1–4 Hz (Rao et al. 2000; Meier 2005). As the power of the corona (Compton scattered emission) increases, the power in the PDS increases at higher frequency ($\nu \geq 0.1$ Hz) and the QPO frequency decreases. Figure 2 shows PDS spectra observed on 2001 July 11 and 1998 April 28. The Compton...
scattered flux increases from $1.5 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$ on 2001 July 11 to $1.9 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$ on 1998 April 28, while the observed QPO frequency decreases from 2.4 Hz on 2001 July 11 to 1.4 Hz on 1998 April 28. It is clear from Figure 2 that the power at $\nu > 0.2$ Hz is less in the PDS observed on 1998 April 28 than in that observed on 2001 July 11. The fast variability is suppressed by photon scattering in the enhanced wind on 1998 April 28 and hence reduces the power in the PDS at higher frequencies. Shaposhnikov & Titarchuk (2006) have discussed the decrease in the PDS power observed in Cyg X-1 at higher frequency ($\nu > 0.1$ Hz) as wind increases. In Cyg X-3, the PDS power in the low hard state drops to below $10^{-3}$ (rms/mean)$^2$ Hz$^{-1}$ at frequencies $\nu > 0.1$ Hz as dense wind from the companion always envelops the compact object (Yadav 2006).

Kotani et al. (2000) analyzed ASCA data of two GRS 1915+105 observations in the low hard state in 1994 and 1995 and detected characteristic absorption lines that suggest large values of $N_H$. They have discussed radiation-driven wind from the accretion disk as the source of enhanced $N_H$ and estimated wind terminal velocity of the order of $10^8$ cm s$^{-1}$ for the values of $r$ and $L_X$ discussed above. They have speculated on the wind’s role in the formation of superluminal radio jets. The spectral analysis of energy spectra during the extended low state requires large $N_H$, which lends further support for the radiation-driven wind from the accretion disk (Yadavale et al. 2002). The evidence for a Seyfert-like warm absorber have been found in other microquasars, such as GRO J1655−40, GX 339−4, and XTE J1650−500, besides GRS 1915+105 (Miller et al. 2004; Ueda et al. 1998; Lee et al. 2002; Kotani et al. 2000), and superluminal flares have been observed in all these sources except XTE J1650−500. In Figure 6, we plot the integrated radio flux of the superluminal flare as a function of $N_H$ calculated from the X-ray data during the preceding plateau state. It brings out clearly the connection between the superluminal flare and the enhanced $N_H$ with a correlation coefficient of 0.90. The dotted line is a linear fit to the data. The wind density for a typical 1 AU sphere comes out to be $\sim 10^9$ cm$^{-3}$, which is similar to the value proposed for quasars (Elvis 2000).

The presence of a dense absorber close to the vicinity of the accretion disk should affect the IR emission during the radio plateaux. The source size of the steady compact jet during the radio plateau state varies as a function of frequency, which is consistent with self-absorbed steady outflow (Dhawan et al. 2000; Fuchs et al. 2001b; Fender et al. 2004). It is similar to the self-absorbed discrete outflows in the case of oscillations/baby jets that produce delayed emission at lower frequencies (Mirabel et al. 1998; Eikenberry et al. 1998; Ishwara-Chandra et al. 2002; Ueda et al. 2002). In both cases, the radio emission is flat or inverted. The IR emission during radio plateaux in GRS 1915+105 (Fuchs et al. 2003a, 2003b) is closer to the IR emission in Cyg X-3, where wind from the companion always envelops the compact object (Ogley et al. 2001; Koch-Miramond et al. 2002).

Our results support the internal shock model for the origin of superluminal flares (Kaiser et al. 2000). The internal shock should form in the previously generated slowly moving wind from the accretion disk with $\beta \leq 0.01$ (Kotani et al. 2000) as the fast-moving discrete jet with $\beta \sim 1$ (Dhawan et al. 2000) catches up and interacts with it. Both the components, the slow-moving wind and the fast-moving jet, are related to the accretion disk during the plateau state, and the strength and speed of these two components will determine the power of the internal shock. This aspect has been brought out clearly by the correlations presented in Figures 3, 4, and 6. In our case the Lorentz factors $\Gamma_2 - 1 \Gamma_1 \sim \Gamma_1$ for these two components (Fender et al. 2004; Rees & Meszaros 1994). The wind deposits large amounts of energy as $\dot{m}_{\text{wind}}$ approaches $\dot{m}_{\text{accr}}$ prior to the switching on of the superluminal flare. GRS 1915+105 produces up to 1 Jy superluminal flares with apparent velocity, $\beta_{\text{app}}$, in the range 1.2−1.7. It is an efficient internal shock scenario in which not just velocity but total jet power has significantly increased (Fender et al. 2004). This view is further strengthened by the fact that Cyg X-3 can produce superluminal flares with flux density up to 15 Jy with $\beta_{\text{app}} \sim 0.69$, where the companion star can provide denser wind. The internal shock model can easily accommodate the high jet power requirement $\geq 10^{38}$ ergs s$^{-1}$ (Fender et al. 1999) and can explain the shifting from thick to thin radio emission during superluminal flares (Kaiser et al. 2000).

Radio plateaux occur when $\dot{m}_{\text{accr}}$, as inferred from the X-ray flux, is very high and $L_{\text{bol}}$ approaches $L_{\text{Edd}}$. As $\dot{m}_{\text{accr}}$ rises, the accretion disk passes through an instability zone (prior to the plateau state) and produces preplateau flares (see Fig. 1). Thereafter, it enters a steady plateau state. At the end of the plateau state, changes in $\dot{m}_{\text{accr}}$ again produce instabilities in the accretion disk, which produce a postplateau flare (flare that produces a superluminal flare), and the source comes out of the plateau state. It may be noted here that a postplateau flare may not always end the plateau state, but it may change the level of the plateau as is the case of superluminal flares on 1998 April 13 and 30 (plateau radio flux of 91 mJy [highest flux in Table 1]). The instabilities in the accretion disk may be triggered either by a change in $\dot{m}_{\text{accr}}$ or by some adjustment among different accretion flows (Yadav et al. 1999). This view is supported by the finding that certain X-ray variability classes are observed preferably before and after the plateaux (low hard state; Naik et al. 2002).

Our results presented here suggest only three types of radio emission in GRS 1915+105: (1) radio emission during the steady plateau state with $\beta$ in the range 0.1−0.4 (steady X-ray properties), (2) oscillations or discrete baby jets with $\beta \sim 1$ (state transition in X-rays), and (3) faint flares of 2–3 minute durations with likely low $\beta$ (hard X-ray spectrum changes but no state transition; Rothstein et al. 2005, Eikenberry et al. 2000). The superluminal flares are the consequences of class 1 and class 2 radio emissions when they occur in this order (but not in the reverse order). Our description of superluminal flares here can explain why the axis of superluminal flares differs by $\leq 12^\circ$ from the axis of AU-scale compact jets (Dhawan et al. 2000). The wind is

![Fig. 6.—Correlation between the integrated radio flux of the superluminal radio flares and the absorption column density, $N_H$, calculated from X-ray spectral analysis of RXTE PCA/HEXTA data during the preflare plateau state. The dotted line is a linear fit to the data.](image-url)
radiation-driven and is expected to originate from the inner part of the accretion disk, while the compact jets are most likely to originate from the outer corona. The phase lag between the hard and soft X-ray photons in GRS 1915+105 changes sign during the plateau state and produces complex behavior (Muno et al. 2004). Varniere (2005) has suggested that anything located inside the inner radius of the accretion disk (in our case wind) that can absorb a small part of soft X-ray flux can explain the changing of sign of the lag and its complex behavior during the plateau state. Another consequence of our results is that one would not expect the oscillations/baby jet type of IR and radio emission in Cyg X-3 (not observed so far; Dhawan et al. 2000) as has been observed in GRS 1915+105 (Mirabel et al. 1998; Eikenberry et al. 1998; Ishwara-Chandra et al. 2002). Any discrete jet (including oscillations) should produce an internal shock as wind from the companion is always present in the case of Cyg X-3, and therefore such jet would always end up producing a superluminal jet with thin radio emission.

The physics in all the systems dominated by black holes is essentially the same, and therefore it is always tempting to compare microquasars with massive extragalactic AGNs and quasars. The correlation between radio and X-ray luminosity during the low hard state (Gallo et al. 2003) can be extended to the AGNs by including a black hole mass term (Merloni et al. 2003; Falcke et al. 2004). Therefore, the steady jets in microquasars during radio plateaux are directly comparable with those in AGNs. Marscher et al. (2002) have claimed to observe an oscillation radio jet (~1 yr⁻¹) in the AGN 3C 120. They related these radio jets to superluminal ejection events, which can be understood in the framework of the model discussed here (if we assume the presence of a warm absorber). The results discussed in this paper suggest the propagation of a shock wave to produce the superluminal jets in microquasars, a interpretation usually favored for jets in extragalactic systems. It has been shown recently that the jets in microquasars are as relativistic as AGN jets provided the jets in microquasars are not confined and the derived opening angles are solely due to the relativistic effect (Miller-Jones et al. 2006; Gopal-Krishna et al. 2004).

It is natural to associate (although it is disputed!) the radio-loud and radio-quiet dichotomy observed in AGNs with the jet-producing low hard state and non–jet-producing high soft state in microquasars (Maccarone et al. 2003). The PDS of luminous narrow-line Seyfert 1 AGNs appears to be similar to that observed during the high soft state in microquasars, while the PDS of the low-luminosity AGNs is similar to that observed during the low hard state in microquasars (McHardy et al. 2004; Markowitz & Uttley 2005). Shocks are related to the most energetic processes in the universe (gamma-ray bursts, large superluminal jets in microquasars and AGNs), and microquasars provide a great opportunity to study them under the best possible conditions within reasonable time.

4. CONCLUSIONS

We present for the first time clear evidence of a direct connection between the accretion disk during plateaux and the following superluminal radio flares. We find that the η_{acc,CR}, as inferred from the X-ray flux, is very high during the radio plateaux and L_{bol,CR} approaches L_{Edd}. We suggest that such hot accretion disks during the radio plateaux are always accompanied by radiation-driven wind. The internal shock forms in the previously generated slowly moving wind from the accretion disk with β ≤ 0.01 as the fast-moving discrete jet with β ~ 1 catches up and interacts with it. Both the components, the slow-moving wind and the fast-moving jet, are related to the accretion disk during the plateau state, and the strength and speed of these two should determine the power of the internal shock. In GRS 1915+105, it is an efficient internal shock scenario in which not just velocity but total jet power has significantly increased. The superluminal flares have steep radio spectra and are observed at large distances from the compact object (≥240 AU). The profile of the superluminal radio flares can be described as fast rise and exponential decay (FRED).

The other radio flares observed in GRS 1915+105 include the persistent radio emission during the plateaux (20–160 mJy), the radio oscillations and discrete radio flares (5–150 mJy), and the preplateau radio flares (50–360 mJy). All of these are observed close to the compact object (<200 AU) and have flat or inverted radio spectra. During the radio plateaux, both the radio flare and the accretion disk are in a steady state (outflow and inflow in the accretion disk are in equilibrium), and a tight correlation is observed between the radio luminosity and the X-ray luminosity as discussed above. The IR and radio oscillations (5–150 mJy) are periodic ejections of adiabatically expanding self-absorbing synchrotron clouds (Mirabel et al. 1998; Ishwara-Chandra et al. 2002). The IR flux suggests that the ejected matter decouples from the accretion disk at the time of the spike in the X-rays (Eikenberry et al. 1998). The preplateau radio flares (50–360 mJy) are discrete ejections that are closely spaced in time and hence produce overlapping radio flares. The preplateau flares have been modeled as adiabatically expanding self-absorbing clouds ejected from the accretion disk, which explain reasonably well all the available observed data of the time delay for radio emission at lower frequencies (Ishwara-Chandra et al. 2002). It is widely believed that it is the coronal material and not the disk material that is ejected prior to radio flares (Rau & Greiner 2003; vadawale et al. 2003; Fender et al. 2004; Rothstein et al. 2005). During oscillations/discrete flares and the preplateau flares, the coronal mass ejections affect the hard X-ray component (Compton component) either partly or completely (state change; outflow and inflow are not in equilibrium in this case unlike during the plateaux).

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