Astron. Astrophys. 362, 691–696 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Disk-jet connection in GRS 1915+105: X-ray soft dips as cause of radio flares

S. Naik and A.R. Rao

Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai, 400 005, India (snaik@cygnus.tifr.res.in; sachi@tifr.res.in)

Received 30 June 2000 / Accepted 24 August 2000

Abstract. We have examined the radio emission characteristics of the micro-quasar GRS 1915+105 during its X-ray emission states as classified by Belloni et al. (2000). We find that the radio emission is high during the χ_1 and χ_3 states (the radio "plateau" state) and also during the β and θ states when X-ray soft dips are present in the X-ray light curve. For all the other X-ray states we find that the radio emission is low ($<$ 20 mJy at 2.25 GHz). This result supports the suggestion made by Naik et al. (2000) that the radio flares are caused by a series of X-ray dip events. To further confirm this result, we have made a systematic study of all the PCA RXTE observations for those days when a radio flare was present. We find 11 such observations and find that all of them are of class β, θ or χ. Further, we have classified all the RXTE PCA observations obtained from 1996 November to 2000 February (when the radio data is available) and confirm that the radio flux, on an average, is much higher during the states β, θ and χ. Based on these results, we argue that the radio flares are caused by the X-ray dips in the source.

Key words: accretion, accretion disks – black hole physics – X-rays: stars – stars: individual: GRS 1915+105

1. Introduction

The Galactic micro-quasar GRS 1915+105 was discovered in 1992 with the WATCH instrument on-board the GRANAT satellite (Castro-Tirado et al. 1992). Subsequent radio observations of the source showed the presence of first superluminal radio source at a distance of 12.5 $\pm$ 1.5 kpc in our Galaxy (Mirabel & Rodriguez 1994). The source is beleived to be a black hole because of the similarities in the spectral and temporal properties with the other superluminal Galactic radio source GRO J1655$-$40 (Zhang et al. 1996).

GRS 1915+105 is a bright X-ray source, emitting at a luminosity of more than 10^{39} erg s^{-1} for extended periods. Observations with BATSE on CGRO (Harmon et al. 1994) and with SIGMA on Granat (Finoguenov et al. 1994) showed the highly variable nature of the source in the hard X-rays. QPOs are seen in the power density spectra of the source in the frequency range of 0.001 $-$ 64 Hz (Morgan et al. 1997). Chen et al. (1997) found that the narrow QPO emission is a characteristic property of the hard branch which is absent in the soft-branch. Muno et al. (1999) found that the low-frequency QPOs (0.5 $-$ 10 Hz) can be used as a tracer of the spectral state of the source.

From radio observations, Mirabel & Rodriguez (1994) found that GRS 1915+105 produces double-sided relativistic ejections of plasma clouds which appears to have superluminal motions. Pooley & Fender (1997) have done a systematic monitoring of the source at 15 GHz with the Ryle Telescope and found periodic oscillations in the range 20 $-$ 40 minutes. From simultaneous observations at different wavelengths, the correlation between the X-ray variability and the emission at radio and infrared wavelengths is established (Pooley & Fender 1997; Fender et al. 1997; Fender & Pooley 1998; Eikenberry et al. 1998; Mirabel et al. 1998; Fender et al. 1999). They showed that the observed multi-wavelength behavior is consistent with the scenario of plasma ejection from the instabilities in the inner accretion disk of the black hole which expands away from the source adiabatically producing radio jets.

Recently, Naik et al. (2000) have reported the detection of a series of X-ray dips during a huge radio flare of strength 0.48 Jy (at 2.25 GHz). They argue that a large number of such X-ray dips can account for the radio flare emission. To investigate whether such X-ray dips are indeed present during other radio flares, in this paper we present a detailed analysis of the association of X-ray intensity states with the radio emission. We use the classification of X-ray intensity states suggested by Belloni et al. (2000) and find that the high radio emission is uniquely identified with only 3 X-ray intensity states: the radio-loud hard state or the "plateau" state (see Fender et al. 1999) and the β and θ states, when X-ray dips are present.

2. Analysis and results

Belloni et al. (2000) have classified all the publicly available RXTE/PCA observations from 1996 January to 1997 December into 12 different classes. The classification is based on the structure of the X-ray light curve and the nature of the color diagram. The X-ray variability characteristics range from steady emission for long durations (classes ϕ and χ), short period flickering variability at different amplitudes (classes γ, μ and δ), large amplitude variations called inner disk oscillations (Belloni

Send offprint requests to: S. Naik

Table 1. Available radio flux during the PCA observations of different classes

Class	No. of Obs	Radio flux Avg.	at 2.25 Min	GHz (Jy) Max	Radio flux Avg.	at 8.3 Min	GHz (Jy) Max
α	7	0.014 ± 0.002	0.007	0.027	0.015 ± 0.003	0.007	0.031
β	9	0.119 ± 0.052	0.008	0.342	0.076 ± 0.027	0.008	0.185
γ	5	0.009 ± 0.0005	0.007	0.010	0.008 ± 0.0008	0.006	0.010
δ	3	0.010 ± 0.0025	0.007	0.015	0.007 ± 0.001	0.005	0.009
κ	1	0.004	0.004	–	0.013	0.013	–
λ	1	0.012	0.012	–	0.013	0.013	–
μ	3	0.008 ± 0.0001	0.008	0.008	0.011 ± 0.003	0.007	0.019
ρ	6	0.008 ± 0.0007	0.005	0.010	0.008 ± 0.0005	0.006	0.009
$\chi 2$	3	0.013 ± 0.0057	0.007	0.025	0.007 ± 0.0024	0.004	0.012
$\chi 4$	7	0.015 ± 0.0033	0.007	0.027	0.016 ± 0.0043	0.006	0.032

et al. 1997) or regular/irregular bursts (Yadav et al. 1999) where the intensity and hardness ratio are anti-correlated (classes λ, κ and ρ), and large amplitude variations accompanied by soft dips (classes θ and β). The remaining two classes can be treated as variants of the above: class α as source repeatedly moving between class χ and ρ, class ν as class β with much shorter soft dips.

To understand the disk-jet connection in the source, we have collected the radio flux density for these 12 different X-ray intensity classes at 2.25 GHz and 8.3 GHz from the NSF-NRAO-NASA Green Bank Interferometer public domain data. To determine the radio flux density for each class and to compensate the observed delay in X-ray and radio wavelengths (Mirabel et al. 1998), we have selected the radio data in the time range of 2 hours earlier and 6 hours later to the starting time of the X-ray data from RXTE/PCA and taken the average value of the radio flux density (if more than one observation exists) over the selected time range for each observations. Finally the flux densities of each observation in a class were averaged out to get the flux density for that class. Out of 163 observations, analyzed by Belloni et al., there are 89 RXTE/PCA observations after 1996 November 22, the starting of GBI radio data. As the radio data are not continuous, out of these 89 observations, radio data are available only for 44 observations in the above selected time range. However, for observations in classes θ, ν, ϕ, $\chi 1$ and $\chi 3$, GBI radio data are not available in the selected time range.

From the RXTE/ASM light curve of the source (Fig. 9, Belloni et al. 2000), the subclasses $\chi 1$, $\chi 2$ and $\chi 3$ are extended and well separated. Although the radio data do not exist for the PCA observations in the selected time range for $\chi 3$, the flux density is taken from the GBI data in the time range as shown in the Fig. 9 of Belloni et al. (2000). The flux density for classes θ, ν, ϕ and $\chi 1$ were taken from Fig. 1 of Pooley & Fender (1997). To get the flux density at 8.3 GHz corresponding to the values at 15 GHz in Fig. 1 by Pooley & Fender (1997), we have used the relation given by Mirabel et al. (1998). The flux density at 2.25 GHz and 8.3 GHz for all the 12 classes is shown in Fig. 1. The upper panel shows the average flux density at 2.25 GHz and the lower panel shows at 8.3 GHz for different classes. The classes for which the data are taken from Pooley & Fender (1997) are marked by an asterisk in the figure to identify from the others.

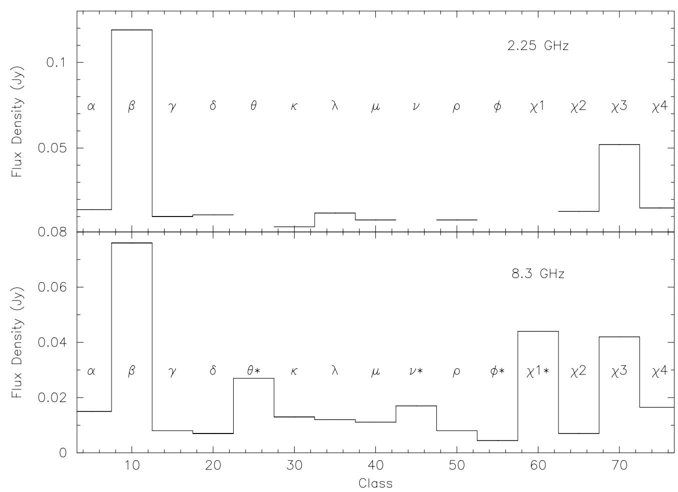

Fig. 1. The average radio flux for GRS 1915+105 at 2.25 GHz (upper panel) and 8.3 GHz (lower panel) for all the twelve classes of X-ray observations, classified by Belloni et al. (2000) during the period 1996 June to 1997 December. The radio data is taken from NSF-NRAO-NASA Green Bank Interferometer public domain data. The data for classes marked by an asterisk are derived from the 15 GHz data (Pooley & Fender 1997).

The details of the radio observations are given in Table 1. Out of 15 different classes of PCA observations (including 4 subclasses of χ), the GBI radio data are available for 12 classes of observations in the above selected time range. From the table, it is seen that the average radio flux densities are $\sim$ 120 mJy at 2.25 GHz and $\sim$ 80 mJy at 8.3 GHz during the PCA observations of class β. The observed maximum and minimum radio flux density during the PCA observations of class β are found to be 342 mJy and 8 mJy at 2.25 GHz and 185 mJy and 8 mJy at 8.3 GHz respectively. Out of 9 PCA observations of class β, during 6 observations, the average flux densities at 8.3 GHz are found to be more than 37 mJy with a maximum of 205 mJy and during the other 3 observations, the flux densities are $\simeq$ 10 mJy. From a careful analysis of these PCA observations of class β with low value of average flux densities, it is seen that the structure of the light curve of only one orbit of each of 2 RXTE/PCA observations are of class β. For the third PCA

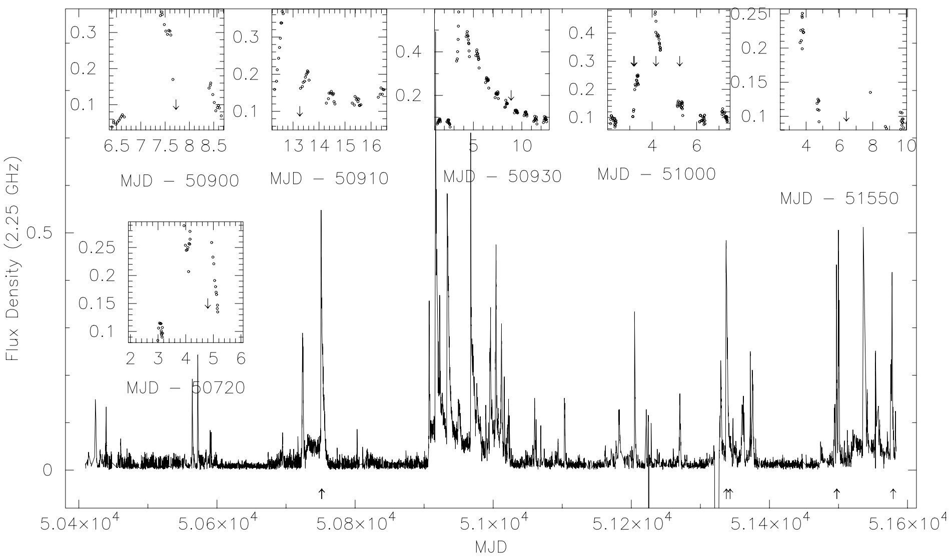

Fig. 2. The presence of soft dips in the X-ray light curve of GRS 1915+105 from RXTE/PCA during the huge radio flares observed with GBI is marked with arrows. The RXTE/PCA observations when class χ was was present (see text) are shown as arrows in the insets.

observation with low flux density, it is seen that the GBI radio data are not available for about 15 hours after the begining of the X-ray soft dip in the light curve which is supposed to be the cause of the radio flares followed by a flux density of ~ 35 mJy at 2.25 GHz. From the table, however, it is seen that the average flux densities at 2.25 GHz during the PCA observations of other classes are ≤ 15 mJy. Hence, we can conclude that the radio flux density during the RXTE/PCA observations of class β are high in comparison to the other observations.

From the figure, it is seen that the flux densities for classes β, θ, $\chi1$ and $\chi3$, are higher. It is seen that there was a huge radio flare during MJD 50751 to 50753 during which the average flux density was more than 300 mJy at 2.25 GHz. All the RXTE/PCA observations (3) during this period are of class β. Apart from this huge radio flare, there were several small flares during the X-ray observations of class β. Although in Belloni et al. (2000) classification, there are less number of observations of class θ, a radio flare at 15 GHz was observed (Figs. 1 and 4, Pooley & Fender 1997) during the period of PCA observations in class θ (MJD 50250 $-$ 50254). During class χ, the flux density was steady without any evidence for oscillations and described as “plateau” by Fender et al. (1999). From these results, we suggest that the source is in high radio emission state during the X-ray classes β, θ and χ.

We have verified the above result by considering X-ray data only for radio flares. For this purpose, we define a radio flare as occasions when the flux density stayed above 0.1 Jy at 2.25 GHz for more than half a day. We find a total number of 46 such radio flares in the time range 1996 November 22 to 2000 February 5 and tried to find out the RXTE/PCA observations during these selected radio flares. Out of these 46 radio flares, X-ray data is available for 10 flares. The X-ray light curve during 4 flares are of type θ (3) and β (1), during 5 radio flares, the light curves are of χ type. However the X-ray light curve for one radio flare that occuered during MJD 50923.0 $-$ 50923.8 can not be classified under any class. From the structure of the light curve, it appears to be of class θ. There were no RXTE/PCA observations during the remaining 36 radio flares. The occupation time of these selected flares is found to be 90 days out of which 3 orbits of RXTE/PCA observations ($\sim 40 - 50$ minutes each) contain soft dips of classes β, 4 orbits contain soft dips of class θ and 26 orbits are of class χ. Fig. 2 shows the radio light curve at 2.25 GHz with GBI data. The presence of RXTE/PCA observations of class θ and β during the selected radio flares with flux density more than 0.1 Jy are indicated by arrows. The RXTE/PCA observations of class χ during the 4 radio flares and the other one are shown in the insets of Fig. 2. From these figures, the RXTE/PCA observations are found to be towards the end of the radio flare except for one event during MJD 51003.0 $-$ 51005.4 when the X-ray light curves are in the class χ. This strongly suggest that the radio flaring is closely associated with the occurance of X-ray states θ and β and the high and steady radio emission state, called as “plateau” is associated with the low-hard X-ray state.

In Fig. 3, we have plotted the light curves and hardness ratio (count rate in $5 - 13$ keV energy range/count rate in $2-5$ keV energy range) of one observation from each classes of θ and β. The similarity in both the classes is the presence of soft X-ray dip in the light curve with identical properties i.e. soft spectrum (hardness ratio), absence of the low frequency QPO (refer Fig. 1e and 1f of Muno et al. 1999). These soft dips of period of ~ 100 s are seen only in the classes θ and β out of all 12 classes of Belloni et al. (2000). The presence of soft Dips in the X-ray light curve, associated with the radio flaring, strongly supports the suggestion given by Naik et al. (2000) that the evacuation of matter from the accretion disk during the presence of soft dips in the X-ray light curve produces the radio flares.

We have analyzed all the publicly available data from RXTE/PCA from 1996 November 22 to 2000 February 05 when the GBI radio is available. Out of 333 number of RXTE/PCA observations, there are 17 observations of class β and 20 observations of class θ. The remaining 297 observations pertain to the other classes of Belloni et al. (2000) classification. However, the

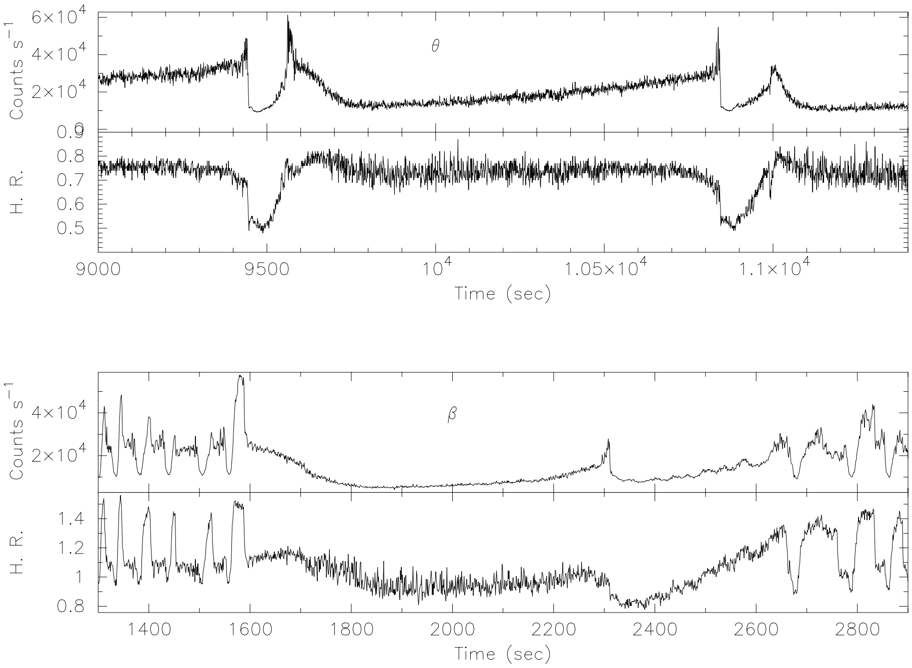

Fig. 3. The X-ray light curve and hardness ratio (H. R.) of GRS 1915+105 obtained from RXTE/PCA observations for the classes θ (1999 June 8) and β (1997 August 31). X-ray dips with low hardness ratio is seen in both the cases.

Table 2. Average radio flux density at 2.25 GHz during the PCA observations of classes β, θ, χ and the rest during 1999 November 22 to 2000 February 5

Class	No. of Obs.	Flux density Avg.	at 2.25 Max	GHz(Jy) Min	Flux density Avg.	at 8.3 Max	GHz(Jy) Min
β	10	0.128 ± 0.046	0.347	0.008	0.080 ± 0.023	0.186	0.008
θ	14	0.041 ± 0.016	0.187	0.008	0.032 ± 0.005	0.074	0.013
$\chi 1/\chi 3$	35	0.096 ± 0.014	0.226	0.009	0.058 ± 0.0062	0.148	0.010
$\chi 2/\chi 4$	20	0.019 ± 0.003	0.054	0.006	0.016 ± 0.002	0.032	0.004
others	95	0.013 ± 0.001	0.048	0.005	0.012 ± 0.001	0.048	0.004

radio flux densities are available only for 174 PCA observations in the above selected time range. The details of the analysis are given in Table 2.

Out of the 17 observations of class β and 20 observations of class θ, the radio flux densities are available only for 10 and 14 observations with the average flux densities of 0.128 Jy and 0.041 Jy at 2.25 GHz and 0.080 Jy and 0.032 Jy at 8.3 GHz respectively in the above selected time range. Similarly out of 297 RXTE/PCA observations of the classes other than β and θ, the radio data are available for 55 observations of class χ. As it is seen from Fig. 1 that the radio flux densities during the PCA observations of subclasses $\chi 1$ and $\chi 3$ are higher than subclasses $\chi 2$ and $\chi 4$, we divided these 55 observations of class χ into 2 subclasses (the PCA observations in subclasses $\chi 1$ and $\chi 3$ into one class and observations in subclasses $\chi 2$ and $\chi 4$ into the other class) based on the RXTE/ASM count rate. The RXTE/ASM count rate for the source during the PCA observations of subclasses $\chi 2$ and $\chi 4$ is found to be ≤ 30 ASM counts whereas during subclasses $\chi 1$ and $\chi 3$, it is ≥ 35 ASM counts. It is found that the average radio flux density at 2.25 GHz for the class $\chi 1/\chi 3$ is 0.096 Jy for 35 PCA observations, whereas it is 0.019 Jy for the other class $\chi 2/\chi 4$ for 20 PCA observations. During the 95 PCA observations of other classes, the average flux density at 2.25 GHz is found to be 0.013 mJy. From this analysis, it is verified that the source remains in a high radio state during the X-ray states of class β, θ and $\chi 1/\chi 3$. During the X-ray state of class $\chi 1/\chi 3$, the source shows a steady and flat spectrum with little oscillations (Fender et al. 1999) in radio bands. Hence, it is verified that radio flares occur mainly in β and θ classes of X-ray states.

3. Discussion and conclusions

The micro-quasar GRS 1915+105 offers a unique opportunity to study the connection between the observed radio jets and the accretion disks which is thought to be present in distant Quasars. Attempts have been made to relate the changes in X-ray emission from the accretion disk with the amount of mater ejected from the system. Belloni et al. (1997) discovered a series of outbursts during which the change in state of the source occurs within $\sim 10 - 100$ seconds and described the change as the appearance and disappearance of the inner accretion disk. Yadav et al. (2000) studied the same burst events and described the two intensity states as the low-hard and high-soft state of the source. The radio flux density during these periods was found be low ($\sim$ 8 mJy at 2.25 GHz). There are certain periods when both the observed flux in X-ray and radio are low and are described as radio-quite hard state (Muno et al. 1999). The periods when both the X-ray and radio fluxes are high without the evidence of any oscillations, are called as radio-loud hard-steady state. Fender et al. (1999) described this class as the "plateau" state. Pooley & Fender (1997) speculated that this plateau state may correspond to the major radio ejections in the source.

Class β is a peculiar type of X-ray emission associated with the change from a high oscillating state to a low-hard state with the presence of a soft dip during the recovery with the characteristics of low intensity and absence of low frequency QPO, followed by a gradual return to the high oscillating state (Belloni et al. 2000). These observations are associated with the synchrotron flares in radio (Mirabel et al. 1998; Fender & Pooley 1998) and infrared (Eikenberry et al. 1998). From simultaneous X-ray and infrared observations, Eikenberry et al. (1998) made a strong argument that the onset of radio/infrared flare is associated with the soft dip rather than the gradual change to the low-hard state. Eikenberry et al. (2000) identified a series of soft X-ray dips (class θ, Belloni et al. 2000) identical with the dips seen during the synchrotron infrared flares, coincident with faint infrared flares. Radio oscillations on a time scale of $20 - 30$ minutes are seen to be accompanied by a series of soft X-ray dips (Fig. 10, Dhawan et al. 2000), similar to the oscillations observed by Fender et al. (1999). Since the soft dip events are associated with the jet emission, Naik et al. (2000) proposed that the huge radio flares are produced by a series of such soft X-ray dips.

It was known earlier that the hard steady state of GRS 1915+105 showed radio emission (the $\chi1/\chi3$ state or the 'plateau' state) with flat spectrum radio emission. It was also know earlier that β and θ states are also associated with radio flares, the so called 'baby jets' (Mirabel et al. 1998; Eikenberry et al. 1998, 2000). It was, however, not known very conclusively what accretion disk characteristics (as observed in X-rays) are associated with steep spectrum radio flares, some of which are observed to be associated with superluminal jet emission. Fender et al. (1999) observed radio oscillations during the start of superluminal ejections and they speculated that the inner disk oscillations give rise to radio oscilations. The present work shows conclusively that the inner disk oscillations (classes λ, κ and ρ) are not associated with radio emission. Naik et al. have pointed out that the source was exhibiting such inner disk oscillations for about a month in 1997 June (Yadav et al. 1999) when the radio flux was consistently below 20 mJy.

Naik et al. (2000) have, for the first time, monitored the source in sufficient time resolution (1 s) for long duty cycles (a few thousand seconds per day, continuously for several days) simultaneously with a radio flare. They detected a series of soft dips (class θ) which are distinctly different from the hard dips of inner disk oscillations. They have speculated that a series of X-ray dips is responsible for the radio flare. Hence the following scenario emerges from the present study: 1) the steady state $\chi1$ and $\chi3$ can give flat spectrum radio source associated with compact (< 10 AU) radio core, 2) The soft X-ray dips can generate small size jet emission and 3) a large collection of X-ray dips causes the radio core to be detached and move out at a super-luminal speed.

We must, however, point out that the association between radio emission and the dip events is of statistical nature. Hence we critically examine below the evidence for this association. If the onset of a huge radio flare (signifying the emission of a superluminal ejecta) is associated with an X-ray emission characteristic observed so far, it has to be necessarily the X-ray dip events. It is, however, quite possible that the X-ray dips do not produce the radio flare due to the following reasons: a) onset of a radio flare does not produce any observable X-ray emission characteristics or b) onset of a radio emission produces a new type of X-ray emission characteristic which has not been observed so far and c) the X-ray dip events could be the manifestations of a disturbed accretion disk, after the production of an ejecta. We argue here that none of these scenarios are likely.

Fender et al. (1999) have worked back the onset time of the superluminal blobs and found that the source was showing 20–30 minute radio oscillations. Such a short time scale should be arising from regions close to the compact object and hence it is very unlikely that the X-ray emission characteristics will remain unaffected. It should be noted here that radio oscillations at similar periods are observed along with a series of X-ray dip events (see Fig. 10. of Dhawan et al. 2000). The radio ejecta contains energy of $\sim 10^{43} - 10^{44}$ ergs and hence the accretion disk event responsible for it should last for about 12 hours (see Fender et al. 1999). Since there are 46 radio flares (above 0.1 Jy) during the GBI monitoring period, it is extremely unlikely that such an event has gone unnoticed so far. Hence we can conclude that presence of a collections of X-ray dips are responsible for the radio flare and consequently the jet emission. A continuous X-ray monitoring during a radio flare should clarify these questions.

Acknowledgements. We thank the members of the RXTE and NSF-NRAO-NASA GBI team for making the data publicly available. The Green Bank Interferometer is a facility of the National Science Foundation operated by the NRAO in support of NASA High Energy Astrophysics programs. We thank P. C. Agrawal for his useful comments.

References

Belloni T., Mendez M., King A.R., et al., 1997, ApJ 479, L145
Belloni T., Klein-Wolt M., Mendez M., et al., 2000, A&A 355, 271
Castro-Tirado A.J., Brandt S., Lund N., 1992, IAU Circ., 5590
Chen X., Swank J.H., Taam R.E., 1997, ApJ 477, L41
Dhawan V., Mirabel I.F., Rodriguez L.F., 2000, ApJ submitted
Eikenberry S.S., Matthews K., Morgan E.H., et al., 1998, ApJ 494, L61
Eikenberry S.S., Matthews K., Muno M., et al., 2000, astro-ph/0001472
Fender R.P., Pooley G.G., Brocksopp C., et al., 1997, MNRAS 290, L65
Fender R.P., Pooley G.G., 1998, MNRAS 300,573
Fender R.P., Garrington S.T., McKay D.J., et al., 1999, MNRAS 304, 865
Finoguenov A., Churazov E., Gilfanov M., et al., 1994, ApJ 424, 940
Harmon B.A., et al., 1994, In: Fitchel C.E., Gehrels N., Norris J.P. (eds.) Proc. 2nd Compton Symp., AIP, New York, p. 210
Mirabel I.F., Rodriguez L.F., 1994, Nat 371, 46

Mirabel I.F., Dhawan V., Chaty S., et al., 1998, A&A 330, L9
Morgan E.H., Remillard R.A., Greiner J., 1997, ApJ 482, 993
Muno M.P., Morgan E.H., Remillard R.A., 1999, ApJ 527, 321
Naik S., Agrawal P.C., Rao A.R., et al., 2000, ApJ (Accepted)
Pooley G.G., Fender R.P., 1997, MNRAS 292, 925
Yadav J.S., Rao A.R., Agrawal P.C., et al., 1999, ApJ 517, 935
Zhang S.N., Robinson C.R., Harmon B.A., et al., 1996, IAU Circ. 6411