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*Letter to the Editor*

# Accretion instabilities and jet formation in GRS 1915+105

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**Abstract.** We report simultaneous observations in the X-ray, infrared, and radio wavelengths of the galactic superluminal source GRS 1915+105. During episodes of rapid disappearance and follow up replenishment of the inner accretion disk evidenced by the X-ray oscillating flux, we observe the ejection of relativistic plasma clouds in the form of synchrotron flares at infrared and radio wavelengths. The expelled clouds contain very energetic particles with Lorentz factors of $\sim 10^3$, or more. These ejections can be viewed as small-scale analogs of the more massive ejecta with relativistic bulk motions that have been previously observed in GRS 1915+105.

**Key words:** accretion, accretion disks: stars: individual: GRS 1915+105 – stars: variables – Infrared: stars – radio continuum: stars – X-rays: stars

## 1. Introduction

The discovery of superluminal jets (Mirabel & Rodríguez 1994) in the black hole X-ray transient source GRS 1915+105 has opened the possibility of studying phenomena in our Galaxy that until recently were believed to be restricted to distant quasars and a few active galactic nuclei. In particular, it has been realized that since the characteristic dynamical times in the flow of matter onto a black hole are proportional to its mass, the events with intervals of minutes in a microquasar could correspond to analogous phenomena with duration of thousands of years in a quasar of $10^9$ $M_\odot$, which is much longer than a human life-time. Therefore, the variations with minutes of duration observed in GRS 1915+105 in the radio, IR, and X rays sample phenomena that we have not been able to observe in quasars.

X-ray observations of GRS 1915+105 with the Rossi X-Ray Timing Explorer (RXTE) revealed remarkable quasi-periodic oscillations (QPOs) that are believed to arise in the accretion disk around a black hole of stellar mass (Greiner et al. 1996, Morgan et al. 1997; Belloni et al. 1997a,b; Chen et al. 1997). Among the diversity of QPOs observed in GRS 1915+105 there is a class of recurrent episodes with amplitude variations of $\sim 10^{39}$ erg s$^{-1}$ (at a distance of 12.5 kpc) in the X-rays, in time scales of one minute to tens of minutes. These QPOs have been attributed to the rapid disappearance and slower replenishment of the inner region of the accretion disk (Belloni et al. 1997a,b). If the accretion is an advection-dominated-flow (Narayan et al. 1997), the disappearing mass will go quietly though the horizon of the black hole. Furthermore, if a fraction of the mass of the accretion disk were blown away, one should see synchrotron emission from expanding clouds in the radio, and perhaps shorter wavelengths.

Although previous observations have shown flares with similar periodicities in the radio (Pooley & Fender, 1997; Rodríguez & Mirabel, 1997a) and infrared (Fender et al. 1997), no truly simultaneous observations in the X-ray, infrared, and radio wavelengths have been reported so far. The observations reported here firmly establish the genesis of expanding clouds of relativistic plasma when GRS 1915+105 recovers from large amplitude dips in the X-ray flux.

## 2. Multiwavelength observations and light curves

In this Letter we report observations made on May 15 and Sept 9, 1997. On May 15 at the UT intervals 6-10 h and 12-16 h, we used the 27 antennae of the Very Large Array (VLA) split in three sub-arrays to allow simultaneous observations at 2, 3.6, and 6 cm. On Sep 9, 17 antennae of the VLA were available for this project, and the observations were done at 3.6 cm only.

The infrared observations were carried out with the United Kingdom Infrared Telescope (UKIRT). On each date, sixty images with the IRCAM3 256×256 InSb detector array, with a K-band filter of 0.37$\mu$m width centered at 2.2$\mu$m, were obtained continuously every 1 min for an interval of $\sim$1.1 h. The 2.2$\mu$m flux of GRS 1915 + 105 on time bins of 1 min was computed using relative photometry with several stars in the field and calibrated with well known standard stars. The infrared fluxes were dereddened assuming $A_K$=3.3 mag (Chaty et al. 1996).

The X-ray observations were done with the PCA on RXTE. It consists of five nearly identical proportional counter units with detectors sensitive to X-rays between 2 and 60 keV.

The results for May 15 are shown in Fig. 1. The RXTE observations exhibit large amplitude variations with sudden drops of the flux into dips of $\sim$5000 counts $s^{-1}$ that last for at least 40 min. The recovery of the X-ray flux from the dips sometimes ends in sharp peaks that reach $\sim 10^{-7}$ erg $cm^{-2}$ $s^{-1}$ (2 mJy) with typical durations of $\sim$25 s. These rebounds of the X-ray flux are followed by smaller amplitude oscillations of $\sim$60 s period that last tens of minutes. At the time of an X-ray gap around 14 h UT, an infrared flare of 12 mJy was observed. The rise of the X-ray flux observed after 14.25 h UT suggests a dip during that gap. Interpolating the pattern, a sharp peak and sequences of oscillations would have occured at $\sim$13.7 h UT.

The quasi-periodic oscillations in the radio flux are typical of the optically thick radio core state, usually observed when the source oscillates between 10 and 100 mJy. A time-shift of the flux peaks, with the short wavelengths peaking first, is clearly observed.

The results for Sep 9 are shown in Fig. 2. The PCA count rates show large amplitude oscillations ($\sim 10^{39}$ erg $s^{-1}$) every $\sim$50 s for intervals of tens of minutes, which are followed by sudden drops into dips. The recovery from the dips is slower than the time of decay and lasts a few tens of minutes. In the X-ray light curves of May 15 and Sep 9 we note the following similarities: 1) both the $\sim$60 s oscillations on May 15 and the $\sim$50 s oscillations of Sep 9 disappear during the dips, and 2) the low intensity value in both cases is about 5000 counts $s^{-1}$, which is well above the background rate of 100 counts $s^{-1}$. However, there are obvious differences between the light curves in the two dates. 1) On May 15 the X-ray dips lasted longer than on Sep 9. 2) On May 15 the infrared flare had smaller amplitude and duration than the radio flare, whereas on Sep 9 they had similar amplitude and duration. 3) On May 15 the time-shift between the infrared peak and the following peak at 3.6 cm is 40 min, on Sep 9 it is 16 min.

The relation between the X-ray, infrared, and radio light curves for Sep 9 is shown in more detail in Fig. 3. The X-ray spectral index (13-60 kev)/(2-13 keV) suddenly increased at the beginning of the dip. Despite the $10^4$ order of magnitude difference in wavelength, the infrared flare and the follow up radio flare are strikingly similar in amplitude, duration, and slope of the increasing and decreasing fluxes. The infrared flare seems to start during the recovery from the X-ray dip at $\sim$8.23 h UT, when the X-ray spectrum softened again and an X-ray spike was observed. The rise of the infrared flux to maximum value continues for a few minutes after the 50 s oscillations in the X-ray flux appeared again.

## 3. Infrared synchrotron precursors

The radio emission from GRS 1915+105 during 1997 May 15 shows a behavior consistent with that expected for synchrotron emission from an adiabatically expanding cloud (van der Laan 1966). In all four bursts observed in the period of 6 to 16 h UT, the light curves at 6, 3.6, and 2-cm reach their peaks with the characteristic wavelength-dependent delay (the short wavelengths peaking first). These delays rule out the possibility that the observed events were produced by time-variable free-free opacity, as proposed by Rodríguez & Mirabel (1997a) to explain sinusoidal variations observed in 1995, since in this model no wavelength-dependent delays are expected. When the formation of clouds is faster than the decay of the flux, consecutive radio events blend together and the integrated emission from GRS 1915+105 may appear with a sinusoidal modulation (Rodríguez & Mirabel, 1997a).

In the van der Laan (1966) model, we can estimate $p$, the energy spectral index of the relativistic electrons ($N(E) \propto E^{-p}$), from the equation that relates the observed maximum flux density, $S_{m,\lambda}$, at a given wavelength, i.e, $S_{m,\lambda} \propto \lambda^{-(7p+3)/(4p+6)}$. For this estimate we use the last burst observed on May 15 between 14 and 16 h UT, since it appears to be more isolated than the others. Since $S_{m,6cm}$ = 39 mJy, and $S_{m,3.6cm}$ = 51 mJy, we obtain $p \simeq 0$.

The ejection is defined to occur at $t = t_0$. The time $t_{m,\lambda}$ since ejection in which the light curve at a given wavelength reaches maximum is given by $t_{m,\lambda} \propto \lambda^{(p+4)/(4p+6)}$. With $p \simeq 0$ we obtain $t_{6cm}/t_{3.6cm}$ = 1.4. Furthermore, from the data in Fig. 1, we have $t_{6cm} + t_0$ = 14.95 h UT and $t_{3.6cm} + t_0$ = 14.70 h UT. Therefore, $t_{6cm} - t_{3.6cm}$ = 0.25 h, and $t_{6cm} \simeq$ 0.9 h. We then find that the ejection of the plasma occurred at $t_0$ = 14.05 h UT.

In this simple model, the UT time of maximum flux density at a given wavelength, for the particular event analyzed above, is given by $t_{m,\lambda}(UT\ h)$ = 14.05 + 0.9$(\lambda/6cm)^{(2/3)}$. Then, the maximum flux density at short wavelengths (i.e. the near infrared) are observed very shortly after the ejection. It is only in the radio wavelengths that significant time delays occur. We note that the 2.2$\mu$m emission indeed reached maximum near 14.0 h UT. This result strongly supports the interpretation of the IR burst on May 15 as the synchrotron precursor of the radio bursts. To our knowledge, this is the first time in X-ray binaries that a clear association is established between an IR synchrotron precursor and the follow-up radio bursts.

## 4. Jet formation during the X-ray dips

Fig. 3 shows that on Sep 9 the infrared flare started during the rise of the X-ray flux from the dip, when a softenning of the spectrum and an X-ray peak were observed. Since at infrared wavelengths

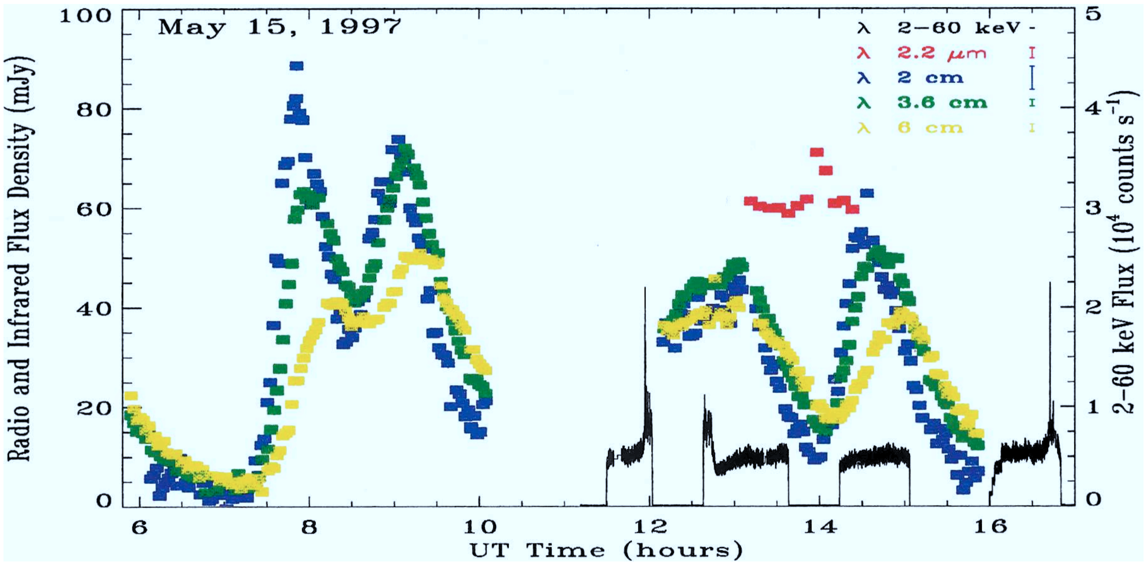


**Fig. 1.** Light curves of GRS 1915+105 for May 15, 1997 obtained with the VLA at 2, 3.6, and 6 cm, with UKIRT at 2.2 $\mu$m, and the PCA of RXTE at 2–60 keV. The time-lag of the peaks as a function of wavelength is the time scale for the clouds to expand and become transparent at longer wavelengths. It is shown that the infrared peak at ∼14 h UT occurred at the time expected for a synchrotron precursor of the peaks at radio wavelengths appearing later in the interval 14.6–14.9 h UT. The infrared flux densities have been dereddened by $A_K$ = 3.3 mag. The units on the left of the vertical axis correspond to the flux densities at radio and infrared wavelengths, those on the right to the X-ray counting rate. Typical error bars for each wavelength are shown at the top right corner. The gaps in the X-ray flux every ∼90 minutes are due to Earth occultations and South Atlantic Anomaly passages.

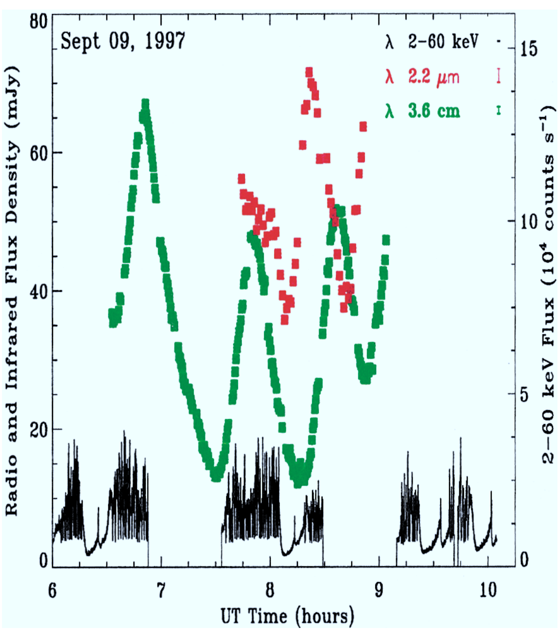


**Fig. 2.** Light curves of GRS 1915+105 for Sep 9, 1997 obtained with the VLA at 3.6 cm, with UKIRT at 2.2 $\mu$m, and the PCA of RXTE at 2–60 keV. A full oscillation of the infrared synchrotron precursor of the following radio outburst is observed. Note the striking similarity of the flares at infrared and radio wavelengths. The units on the left of the vertical axis are for the radio and infrared flux densities, whereas those on the right are for the X-ray counting rate. Typical error bars for each wavelength are shown at the top right corner.

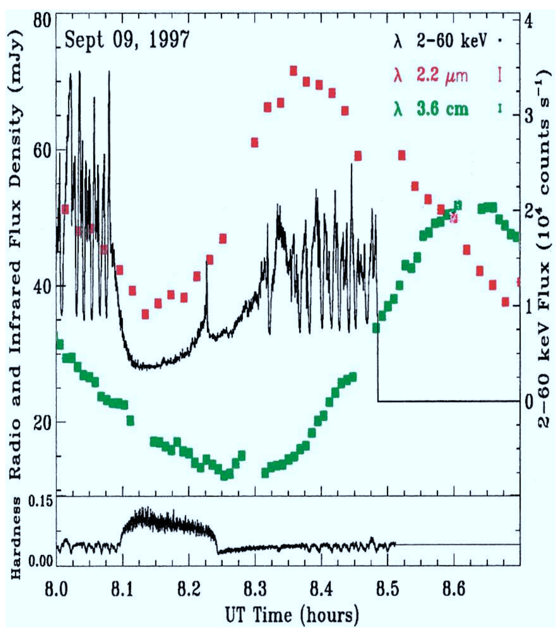


**Fig. 3.** Blow up of the light curves at the time of the infrared flare detected on Sep 9, 1997. The infrared flare starts during the recovery from the X-ray dip, when an X-ray spike was observed. These observations show the connection between the rapid disappearance and follow up replenishment of the inner accretion disk seen in the X-rays, and the ejection of relativistic plasma clouds observed as synchrotron emission at infrared and radio wavelengths. The hardness ratio (13–60 keV)/(2–13 keV) is shown at the bottom.

the ejected plasma becomes transparent very shortly after the ejection, the rise of the infrared flux to maximum indicates that the injection of relativistic particles lasted ∼10 min, or less.

If we assume that the synchrotron emitting plasma expands at $\sim 0.2c$, as observed in a larger scale ejection (Mirabel & Rodríguez 1994), 15 minutes after the ejection the clouds have dimensions of $\sim 10^{13}$ cm. Using this dimension and the infrared and radio flux density values measured on Sep 9, with equipartition arguments we estimate a brightness temperature of $10^{12}$ K, a magnetic field of 16 G, an equipartition energy in relativistic electrons of $5 \times 10^{39}$ erg, and a typical synchrotron luminosity integrated from $2.2 \mu$m to 6 cm of the order of $10^{36}$ erg s$^{-1}$. These parameters are comparable to those derived by Fender et al. (1997) from observations on other epochs. If the electrons that produce the synchrotron radiation have a representative Lorentz factor of $\sim 10^3$, and there is one proton per electron, the minimum mass of the clouds that are ejected every few tens of minutes is $\sim 10^{19}$ g.

For the parameters of these clouds the energy losses are dominated by adiabatic expansion and the clouds should have a lifetime of about 1 h, as observed here. An infrared jet as the one reported by Sams, Eckart & Sunyaev (1996), which reached distances of ∼0.2 arcsec (2500 AU at 12.5 kpc) requires very energetic particles, and a re-acceleration mechanism. We point out that radio blobs with bulk motions of $0.92c$ and lifetimes of several weeks have been observed (Rodríguez & Mirabel, 1997b).

## 5. Conclusions

1) At times of quasi-periodic oscillations of large amplitude in the X-rays, relativistic plasma clouds emanate from the X-ray binary. The time shift of the emission at radio wavelengths is consistent with synchrotron radiation from gas in adiabatic expansion.
2) The association of infrared synchrotron precursors to follow-up bursts at radio wavelengths is firmly established.
3) By the simultaneous observations reported here, we definitively confirm that the infrared and radio flares are associated to X-ray dips, as suggested by Fender et al (1997) and Pooley & Fender (1997). The onset of the ejection takes place during the recovery from the X-ray dip of hard (13-60 keV)/(2-13 keV) spectrum, at the time of a spike in the X-rays.
4) The expanding clouds of plasma reported here can be viewed as small-scale analogs of the more massive ejections associated to large radio outbursts (Rodríguez & Mirabel, 1997b). The equipartition energy in relativistic electrons in the mini-ejecta is of order of $5 \times 10^{39}$ erg, namely, $\sim 10^3$ times less energetic than in major ejecta. However, the genesis of these smaller scale clouds is much more frequent, and may represent an important phenomenon in the long term evolution of the binary and its environment.
5) The multiwavelength variations with minutes of duration in GRS 1915+105 show how the sudden disappearance of the inner accretion disk around a black hole of stellar mass triggers the formation of relativistic expanding clouds. Analogous phenomena in quasars with black holes of $10^9$ $M_\odot$ would require thousands of years of observations. Therefore, microquasars in our own Galaxy can provide new information on the physics of accretion disks around black holes and are thus useful to gain insight into the relativistic ejections seen elsewhere in the Universe.

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## References

Chaty, S., Mirabel, I.F., Duc, P.A., Wink, J.E. & Rodríguez, L.F. 1996, A&A 310, 825.
Chen, X., Swank, J.H. & Taam, R.E. 1997, ApJ 477, L41.
Belloni, T., Méndez, M., King, A.R., van der Klis, M. & van Paradijs, J. 1997a, ApJ 479, L145.
Belloni, T., Méndez, M., King, A.R., van der Klis, M. & van Paradijs, J. 1997b, ApJ in press.
Fender, R.P., Pooley, G.G., Brocksopp, C. & Newell, S.J. 1997 MNRAS, 290, L65.
Greiner, J., Morgan, E.H. & Remillard, R.A. 1996, ApJ 473, L107.
Mirabel I.F., Rodríguez L.F., 1994, Nat, 371, 46.
Morgan, E.H, Remillard, R.A. & Greiner, J. 1997, ApJ 482, 993.
Narayan, R., Garcia, M.R. & McClintock, J.E. 1997, ApJ 478, L79.
Pooley, G. & Fender, R.P. 1997, MNRAS in press.
Rodríguez, L.F. & Mirabel, I.F. 1997a, ApJ 474, L123.
Rodríguez, L.F. & Mirabel, I.F. 1997b, ApJ, submitted.
Sams, B., Eckart, A & Sunyaev, R. 1996, Nat, 382, 47.
van der Laan, H. 1966, Nat, 211, 1131

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