Multi-Wavelength Monitoring of GRS 1915+105

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Abstract. Since its discovery in 1992, the superluminal X-ray transient GRS 1915+105 has been extensively observed in an attempt to understand its behaviour. We present here preliminary results from a multi-wavelength campaign undertaken from July to September 1996. This study includes X-ray data from the RXTE All Sky Monitor and BATSE, two-frequency data from the Nancay radio telescope, and infrared photometry from the 1.8m Perkins telescope at Lowell Observatory. The K-band data presented herein provide the first long-term well-sampled IR light curve of GRS 1915+105. We compare the various light curves, searching for correlations in the behaviour of the source at differing wavelengths and for possible periodicities.

INTRODUCTION AND OBSERVATIONS

The X-ray transient GRS 1915+105 was discovered by the GRANAT satellite in 1992 [1]. VLA observations at the time of outburst led to the discovery of relativistic ejections of plasma clouds with apparent superluminal motions, possibly a smaller-scale analogue to the jets observed in active galactic nuclei and quasars [2]. GRS 1915+105 has a highly variable spectral index and often exceeds the Eddington luminosity limit for a neutron star, indicating that the system may contain a black hole. Radio observations show that it is at a kinematic distance $D = 12.5\pm1.5$ kpc from the Sun; combined with measurements of the hydrogen column density along the line of sight, a visual extinction of $A_V = 26.5\pm1$ mag has been determined [3]. Variable radio and IR counterparts to the X-ray source have been found [4]. However, the optical counterpart has only been detected at $I = 23.4$ [5].

On the basis of its spectral morphology and the calculated absolute K magnitude, Castro-Tirado *et al.* [6] suggested GRS 1915+105 to be a low-mass X-ray binary (LMXB). However, its long term X-ray behaviour has shown erratic burts with recurrent peaks of similar intensity (maximum $L_x = 3x10^{38}$ ergs/s; [3]), unlike typical X-ray light curves of LMXBs [7]. K-band spectroscopy of the counterpart revealed several prominent emission features but no detectable absorption features which would be indicative of a late-type secondary. On the contrary, the K-band spectrum is very similar to those of high-mass X-ray binaries (HMXB) with a Be star as the mass-losing component [8]. In addition, the absolute magnitude and colours of GRS 1915+105 are strikingly similar to other HMXBs, most notably the LMC Be/X-ray binary (XRB) A0538-66 [9].

JHK photometry of the IR counterpart has revealed both short- and long-term variability, but no periodicity has been seen [3]. In order to search for the long-term periodicity (~15-45 days) expected in an eccentric HMXB, a high-resolution (~1 day) light curve with a baseline of several months is necessary. At X-ray and radio wavelengths, GRS 1915+105 shows fluctuations of variable amplitude on a variety of timescales. As in the IR, no consistent periodicity has been found. However, some X-ray and radio observations have shown a quasi-periodicity of ~30 days [10].

We present multi-wavelength light curves of GRS 1915+105 from the period July to September 1996, including K-band photometry obtained with the Ohio State Infrared Imager/Spectrometer (OSIRIS) on the 1.8m Perkins telescope at Lowell Observatory, X-ray data from the RXTE All-Sky Monitor (2-10 keV) and BATSE (20-200keV), and 1414 MHz and 3310 MHz observations from the Nancay radio telescope. This study is the first to include long-term well-sampled IR photometry as well as X-ray and radio information in a multi-wavelength study of GRS 1915+105.

THE INFRARED LIGHT CURVE

The five three-month light curves of GRS 1915+105 we obtained are shown in Figure 1; the K-band curve appears in the top panel. GRS 1915+105 exhibits variability from K ~12.5 to ~13.5, with maxima at UT dates 3 July, 7 August, and 15 September. A visual inspection of the curve between the latter two maxima indicates an apparent 40-day modulation. An attempt to search for a regular periodicity on this timescale was unsuccessful, as a 40-day period appears inconsistent with the ~30 day separation of the first two maxima. However, we note that it is possible that our observations began *after* a true peak; therefore a ~40-day cycle cannot be ruled out. The shape of the curve and the long timescale for the variations are intriguingly similar to several known Be/XRB systems with eccentric orbits and long periods (generally $\gtrsim$20 days; [11]). The IR photometric characteristics of GRS 1915+105 are especially similar to the LMC Be/XRB A0538-66 (X0535-668). Both sources show $\gtrsim$1 magnitude variability at K [8], and both reach $L_x \sim 10^{39}$ erg/s at outburst peak [12,13].

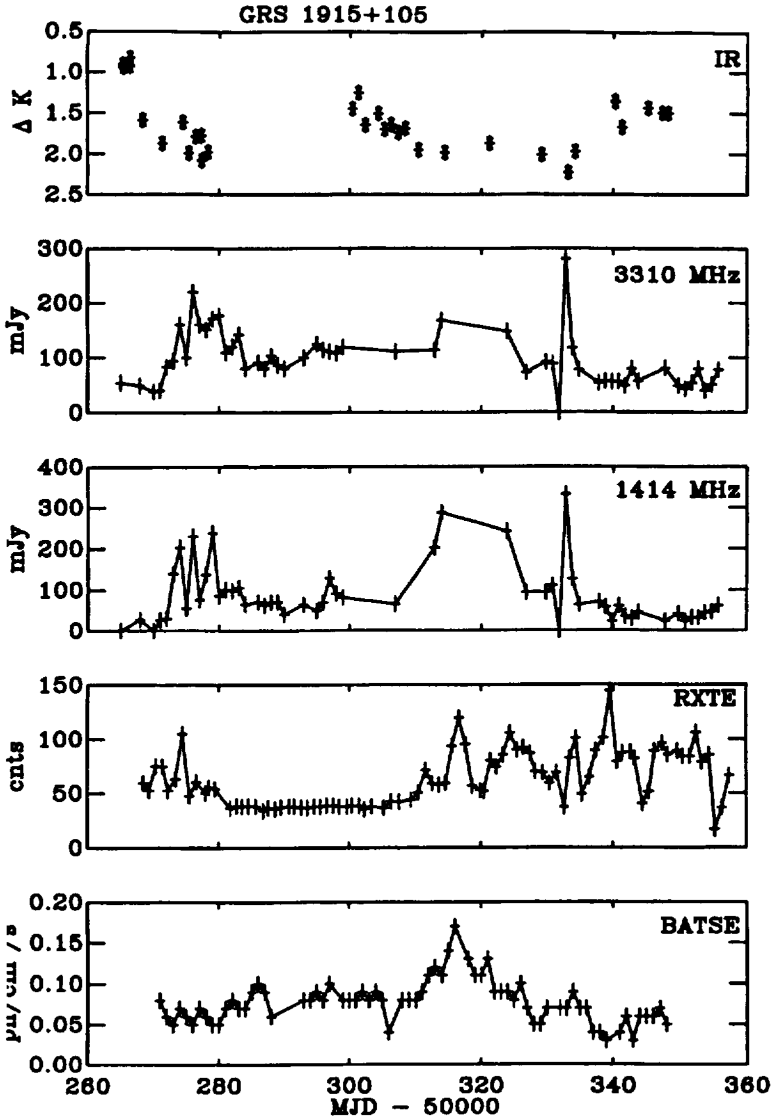

FIGURE 1. Multi-wavelength light curves of GRS 1915+105 from July-September 1996. Note the simultaneous flare of days 310-327 which appears in the radio and X-ray data, but which corresponds to a minimum in the IR light curve.

The inclination of GRS 1915+105 is well constrained to be $i = 70 \pm 2°$from the angle of the jet emission [2]. We therefore expect IR variability on the orbital period due purely to either ellipsoidal modulations and/or X-ray heating of the companion star; however, the amplitude of these variations is partially dependent on the spectral type of the mass-donating star. Substantial orbital flux variations (~1 mag) are generally expected from high-i LMXBs, where the IR light curve is dominated by X-ray heating [14]. In HMXBs, more moderate ellipsoidal variability (~10-20%) is the norm [15]. We note, however, that the Be/XRB A0538-66 shows >1 mag variability at K [9]. In addition, the first maximum in our light curve is ~0.3 mag brighter than the two subsequent maxima, indicating possible short-term variability such as that seen by Chaty *et al.*. It therefore seems likely that the IR variability in our K-band light curve does not result from a single cause, but from several different processes, perhaps with an underlying ~40-day orbital modulation.

In addition to orbital variability, there are a number of possible sources of IR emission in GRS 1915+105 which may account for the observed changes in magnitude. These include (1) IR emission from the accretion disk [6], (2) free-free emission from an X-ray driven wind [16], (3) time-variable Doppler-broadened spectral line emission from ions in the relativistic jets [8], (4) thermal dust reverberation of energetic outbursts [12], and (5) synchrotron emission from relativistic jets [17]. Of these possibilities, (3), (4), and (5) are related to ejection events and would therefore produce changes in the IR magnitude correlated with jet activity. Finally, enhanced IR emission could be produced as a result of advective accretion in the inner accretion disk.

RADIO AND X-RAY LIGHT CURVES

Radio and X-ray light curves for July-September 1996 appear in the lower four panels of Figure 1. While the two radio curves show very similar variability, the RXTE and BATSE data do not show similar behaviour, indicating strong spectral variations. The most striking feature of these light curves occurs at day 310 (15 August), when a flare occurs at all four wavelengths. This flare peaks at day 311 and then falls off over ~15 days in the hard X-rays and radio, while the soft X-rays continue to show large amplitude fluctuations.

On the basis of the similarity in rise, duration, and decay times of the hard X-ray/radio flare during days 310-327 to the April 1994 ejection event reported by Rodriguez *et al.* [18] and the suspected ejection event in August 1995 discussed by Foster *et al.* [19], it seems likely that the flare in our data indicates that an ejection event occurred at this time (August 1996). In the April 1994 and August 1995 ejections of GRS 1915+105, the hard X-ray flux peaks prior to the radio, while in our data, the radio and hard X-ray peaks appear coincident. Our data are not necessarily inconsistent with this pattern, as it is possible that the actual radio peak during the observed flare occurred during the gap in our radio coverage (days 311-325). The pattern of the appearance of a hard X-ray peak followed within a few days by a radio peak, with subsequent correlated decays, may be a signature of jet ejection in GRS 1915+105 (as suggested by Harmon *et al.* [7]). It seems likely, however, that this is not the only such signature. As yet undefined are the mechanisms which are necessary to cause the changes in the hard X-ray/radio behaviour surrounding ejection events, and hence altering the ejection signatures of GRS 1915+105 at various times. What does seem likely is that ejection events do not occur if X-ray (hard or soft) active states are not accompanied by radio emission levels $\gtrsim 100$ mJy [8,20].

CONCLUSIONS

(i) There is evidence for a long-term periodic IR modulation on the order of 30-40 days. The qualitative characteristics of this modulation are similar to those expected for a Be/XRB with an eccentric orbit. However, it is likely that the IR variability arises from a combination of causes, with short-term IR emission superimposed on an underlying orbital period.

(ii) By comparing our X-ray/radio data to previously observed ejection events, we believe that an ejection event took place in August 1996, when we see a large simultaneous outburst in the radio and X-rays. It is interesting to note that during this event the IR emission is at a low level, indicating that IR variations resulting from jet ejection may be minimal in this instance.

(iii) In general agreement with Harmon *et al.* [7], we surmise that the pattern of a hard X-ray flare rapidly followed by a radio flare, with subsequent correlated decays, is a signature of jet ejection in GRS 1915+105; however, the X-ray activity must be accompanied by radio emission levels $\gtrsim$100 mJy. We also note that this is probably not the only such hallmark of ejection events.

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