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Two ROSAT HRI observations of GRO J1655–40

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Abstract. GRO J1655–40 was observed with the *ROSAT* HRI on two occasions: ones (in August 1994) between the first and the second outbursts in 1994, and ones between a soft and a hard X-ray outburst (in March 1995). The first observation allowed to improve the X-ray position, thus confirming the optical and radio identification. In addition, a distance of d≈3 kpc is derived using the dust scattering halo. The combination with radio measurements suggests that the X-ray emission originated in an accretion disk or corona rather then in a jet.
The results of the second *ROSAT* observation and the comparison with earlier TTM observations suggest that the X-rays at this epoch were emitted from an accretion disk.

Key words: X-ray transients – superluminal motion – X-ray binaries – black hole candidates – GRO J1655–40

1. Introduction

GRO J1655–40 was discovered by BATSE on July 27, 1994 (Zhang et al. 1994). Its X-ray intensity rose to about 1.1 Crab (20–100 keV) within about 12 hours and remained at a 0.85 Crab plateau for 11 days. After a slow decrease to 0.65 Crab over a 4 day period it dropped below the detection threshold within another 3 days (Wilson et al. 1994). Emission up to 600 keV was detected by the OSSE instrument on GRO (Kroeger et al. 1994). The spectrum in the BATSE and OSSE range is well represented by a powerlaw model with considerable changes of its slope with time. The spectrum softened during the rise (photon index evolving from –2.5 to –3.0) and hardened over the outburst with the photon index evolving from –3.15 to –2.4 during the first 10 days (middle panel of Fig. 1; Wilson et al. 1994, Kroeger et al. 1994). A sketch of the X-ray lightcurve including the evolution of the photon index is given in Fig. 1 (middle panel).

Further BATSE monitoring showed the source to be in outburst for a couple of days every ≈120 days (Zhang et al. 1995). Radio observations of the 0$^\circ\!\!.$3 radius error box revealed the counterpart at R.A. = $16^h54^m00^s$, Decl.=–39°50′45″(Campbell-Wilson & Hunstead 1994, Hjellming 1994a), and later on multiple relativistic ejections after hard X-ray outbursts (Hjellming and Rupen 1995) were detected.

The optical counterpart was found as a red (probably absorbed) object at V=14.2 mag (Bailyn et al. 1994a,b). No quiescent optical object is visible on the UK Schmidt Survey (V≈18 mag) at this position, and thus the optical outburst amplitude is larger than 4 mag (Bailyn et al. 1994a). The system is eclipsing with a period of 2.6 days, and detailed spectroscopy and photometry results in an mass estimate of the central object of 4–6 $M_\odot$ surrounded by a 1 $M_\odot$ F- or G-type companion (Bailyn et al. 1995).

Here, I summarize the results of two short *ROSAT* target of opportunity observations of GRO J1655–40.

2. The August 1994 observation

Immediately after the notification of the discovery of GRO J1655–40 we attempted for a *ROSAT* TOO. Unfortunately, the *ROSAT* observing window opened only three weeks later, and thus our observation with the high resolution imager (HRI) was not performed before August 28, 1994. Most of the details of this observation have already been published (Greiner, Predehl und Pohl 1995), and therefore only a summary is given here to allow a better comparison with the second *ROSAT* observation described later.

2.1. Position and Intensity

Due to the *ROSAT* observing window, the first outburst of GRO J1655–40 was already over when the HRI observation was performed. Thus, it happened to be just during the "off-state" between the first and the second GRO J1655–40 outburst. Given the position uncertainty during the scheduling process of the observation, we performed three raster pointings to cover the entire BATSE

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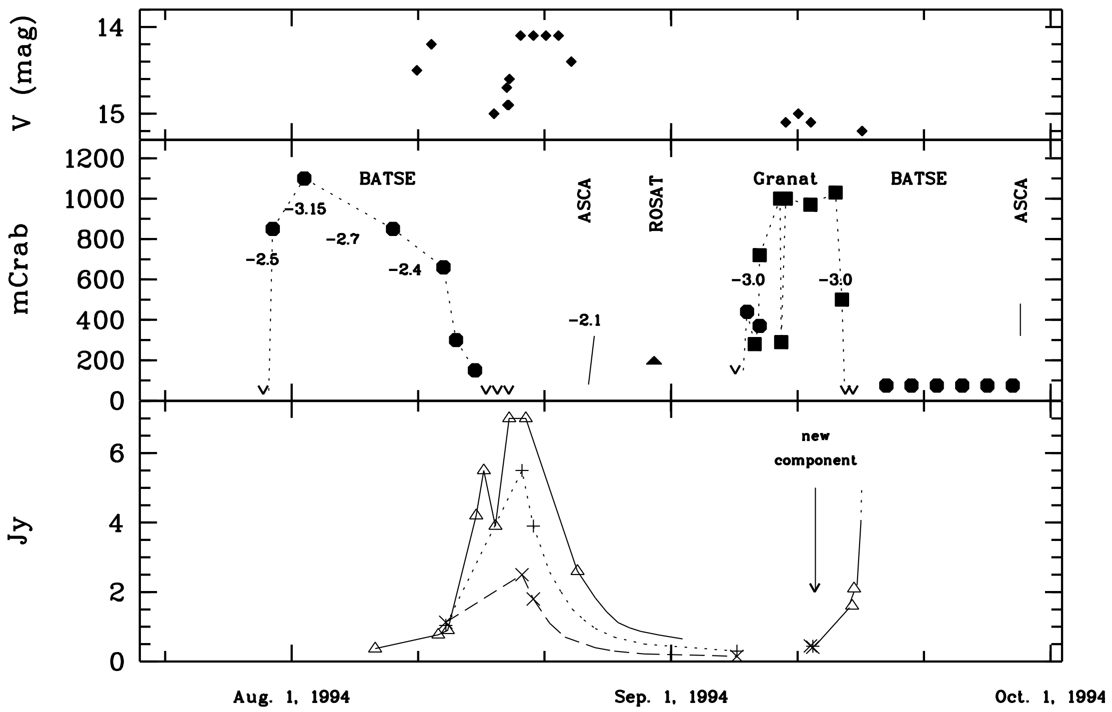

Fig. 1. Light curve of the first two outbursts of GRO J1655–40 at different wavelengths. **Top panel:** in the optical V band (Bailyn et al. 1994a, b; Gonzalez et al. 1994); **middle panel:** at hard X-rays (20–100 keV) from BATSE (Paciesas et al. 1994, Wilson et al. 1994, Harmon et al. 1994) and soft X-rays (8–20 keV) from Granat (Sazonov&Sunyaev 1994); The tilted line shows the range of intensity variation during the pointed ASCA observation (Inoue et al. 1994, Nagase et al. 1994), and the triangle marks the intensity during the *ROSAT* observation. Photon power law indices are displayed below the intensity measurements. **lower panel:** at the three radio wavelengths 843 MHz (solid line), 1.4 GHz (dotted line) and 4.9 GHz (dashed line) (Hunstead et al. 1994; Hjellming 1994a, b; Hjellming&Rupen 1994a, b; Campbell-Wilson et al. 1994).

error box. In one of these pointings, GRO J1655–40 was clearly detected at 4′ off-axis angle. The best fit position (2000.0) of GRO J1655–40 from this *ROSAT* HRI detection is: R.A. = $16^h53^m59\overset{s}{.}9$, Decl. = $-39°50'44''$ with a systematic boresight error of $\pm8''$, completely consistent with the radio and optical position.

The mean HRI count rate during the 782 sec observation interval was determined to be 61 cts/sec. Adopting the spectral parameters of the ASCA observation on August 23, 1994 (i.e. a powerlaw index of –2.1 and an absorbing column of 5×10^{21} cm^{-2}, Inoue et al. 1994), this mean count rate corresponds to about 200 mCrab in the ROSAT band or equivalently an unabsorbed luminosity of 2×10^{37} / (D/3kpc)^2 erg/s (0.1–2.4 keV).

2.2. Dust scattering halo

The observed radial profile of GRO J1655–40 (galactic latitude of bII=$2\overset{\circ}{.}46$) in the HRI is considerably wider than the instrument point spread function due to the scattering of X-rays by interstellar dust. The relative intensity of the halo was determined to 21% at a mean energy E = 1.2 keV. From observations of other X-ray sources having known optical counterparts, correlations of the deduced effective optical depth τ_{eff}(1 keV) with the optical extinction (A_V/τ_{eff}(1 keV)≈17) and with the hydrogen column density ($N_H[10^{21}]$ cm$^{-2}/\tau_{eff}$(1 keV)≈23) have been deduced (Predehl & Schmitt 1995). Applying these relations to GRO J1655–40 results in A_V = 5.6 or N_H=7.0×10^{21} cm^{-2}. Using a mean extinction of A_V = 1.9 mag/kpc (Allen 1973) this implies a distance of GRO J1655–40 of about 3 kpc, and a colour excess $E_{B-V}\approx1.7$ for the optical counterpart.

2.3. Temporal variability

Given the BATSE daily upper limit of about 50 mCrab and assuming that the powerlaw X-ray spectrum in the 1–10 keV range as observed with ASCA 5 days prior to our ROSAT observation had not changed, we conclude that the observed luminosity state cannot have lasted longer than 6 hours. Changes of the powerlaw slope have only little effect on this number unless an additional soft component has developed within these 5 days. The variability timescale of 6 hours implies that the emission region is smaller than a few times 10^{14} cm.

For the lightcurve deduction a much smaller extraction radius (10″) has been chosen in order to avoid the dust halo to smear out temporal variations. Since photons at increasing distances from the central source have travelled longer and thus are emitted earlier any lightcurve of the total detected photons would include an averaging in time of the source intensity. After background subtraction, vignetting and deadtime correction the lightcurve shows no evidence for short-term variability in excess of what is expected according to a Poisson distribution. It is interesting to note that during the main (first) outburst also no low-frequency noise (10–500 mHz) was discovered in the hard X-ray range (Wilson et al. 1994).

In addition, no period could be found in the range 0.01–10 sec, resulting in a 3σ upper limit for the modulation of a sinusoidal signal of 7%.

2.4. Consequences

As in BL Lac objects most of the radio emission from GRO J1655–40 originates from incoherent synchrotron radiation of relativistic electrons in a jet. However, there are several arguments against a jet origin of the X-ray emission of GRO J1655–40.

(1) The predicted synchrotron-self-Compton flux is always much less than the observed value of $\sim$0.3 mJy at 1 keV, if the system size is not smaller than 1 AU ($\sim$ 0.3 mas). This size limit is around an order of magnitude less than what is deduced from the variability timescale. However, in this case the emission regions would be strongly overpressurized in particles compared to the magnetic field. Also, the relevant cooling timescales would be much too long compared to the observed decay timescales of a few days. In this case one has to invoke severe expansion losses as dominant energy loss process, which act independent of energy and hence could explain the similarity in timescales between the radio- and X-ray emission. Adiabatic decompression would also predict the highest X-ray intensity at the beginning of the outburst when the source is most compact. This behaviour harmonizes well with the time lag between the X-ray emission and the radio emission which was optically thick also at high frequencies during the first phase of the outburst.

(2) The steepness of the spectral slope in the hard X-rays (–2.5...–3.5) and the hardening of the spectrum during the X-ray decline are hard to explain on the basis of synchrotron-self-Compton emission, especially when invoking the achromatic adiabatic expansion as main energy loss mechanism. The flux ratio between the X-rays and the radio emission together with the steep X-ray spectrum also does not allow a reasonable modelling of the X-ray flux as synchrotron emission from the same particle distribution that is seen in the radio band.

(3) A suggestive comparison of the galactic superluminal motion sources was proposed with SS433 (Mirabel & Rodrigues 1994). A study of the EXOSAT observations (Watson et al. 1986) of this source has demonstrated that the majority of the X-ray emission, and in particular the iron line emission, must originate in the relativistic jets and be thermal in nature. Given the completely different X-ray spectrum of GRO J1655–40, the lack of prominent X-ray lines (Nagase et al. 1994) and of anomalous optical emission lines (Wagner et al. 1994), SS433 seems not to be like GRO J1655–40 (and/or GRS 1915+105).

Thus, X-ray and radio emission rather certainly originate at different locations in the GRO J1655–40 system. There are two other main locations for X-ray emission: the accretion disk and a hot corona. According to standard theory, the accretion disk is thought to produce a UV or soft X-ray component, part of which is then comptonised by hot electrons in the corona to yield the power law shaped emission spectrum extending to hundred keV or more. Though the ASCA observation on August 23, 1994 did not show any indication for a soft component, one cannot rule out the possibility that such a component built up within five days and gave rise to the observed intensity and variability. If, on the contrary, one assumes no spectral evolution within these five days, then the corona would be a natural source of the X-rays during this epoch.

3. The March 1995 observation

The second target of opportunity observation on GRO J1655–40 was performed during the next *ROSAT* observing window on March 3/4, 1995. The mean HRI countrate was 181 cts/sec. The simultaneously measured mean hard X-ray (BATSE) spectrum at 20–100 keV gives a power law of -2.3 ± 0.3 photon index at about 140 ± 40 mCrab (Harmon 1995). Extrapolating this spectral shape into the *ROSAT* band and using the absorption determined from the dust scattering halo of the first observation predicts a HRI countrate of 50 ± 10 cts/sec. Thus, again the observed GRO J1655–40 intensity at soft X-rays (*ROSAT*) is more than a factor three higher than at hard X-rays (BATSE). And similar to the previous argumentation this fact may be due to either short duration (few hours) high states or an additional soft component.

TTM observations on February 22, 1995 (i.e. 9 days before the *ROSAT* HRI observation) have recorded a blackbody-like spectrum with about 1 keV temperature at 1.7 Crab intensity (Alexandrovich, Borozdin and Sunyaev 1995). In contrast to the observed rapid variability at hard X-rays it seems unlikely that this soft blackbody-like component (usually being explained by the hot part of the innermost accretion disk) has completely decayed within the 9 days. Therefore, the above described difference between the intensities measured simultaneously by *ROSAT* and BATSE can be naturally attributed to this soft component.

As in the previous HRI observation we do not find pulsations or QPOs in the 0.01–10 sec range.

4. Upper Limits

GRO J1655–40 was not detected in a *ROSAT* PSPC pointing in Sep. 1993, giving an upper limit of 3×10^{-3} PSPC cts/sec, i.e. a factor 6×10^{4} lower than the mean flux on August 28, 1994 (including a PSPC/HRI countrate conversion factor of 3). Depending on the assumed quiescent X-ray spectrum this translates into an upper limit of the source luminosity of 1–5×10^{32} / $(D/3\mathrm{kpc})^{2}$ erg/s (0.1–2.4 keV). The source was also not visible during the ROSAT All-Sky-Survey observation (for a total of 325 sec between Aug. 28–30, 1990), giving an upper limit of 0.02 cts/sec.

5. Conclusion

With the short ROSAT HRI observations the X-ray position of GRO J1655–40 could be improved, and was shown to coincide with the earlier proposed radio and optical counterparts. The scattering of X-rays from GRO J1655–40 by the interstellar dust causes a widening of the radial intensity profile which in turn allows to derive a distance of GRO J1655–40 of 3 kpc.

While an origin of the X-ray emission observed in August 1994 is unlikely to be produced in a jet by the same electron distribution as the radio emission, one cannot distinguish between accretion disk or corona origin due to lack of X-ray spectral information. If the emission were from a corona, then the emission region would be smaller than a few times 10^{14} cm. The X-ray emission observed during the March 1995 observation is believed to stem from a hot accretion disk.

Is there a distinct difference between the two galactic superluminal motion transient sources and the usual "black hole" X-ray transients (BHTs)? Observational evidence is mounting that the lightcurves of transient sources are coupled to their spectral state: in the presence of a soft, blackbody-like component (normally interpreted as disk blackbody from the inner accretion disk) besides the hard (powerlaw) component the lightcurves decay exponentially with $\tau \approx$10–30 days, whereas in the presence of only the hard component the intensity variations are more erratic and the decay is much faster (a few days). Thus, the remaining difference between GRO J1655–40/GRS 1915–105 and BHTs are the facts that (1) the outbursts during activity states repeat on timescales of weeks to months whereas the repetition for BHTs is of the order of 10 years, and (2) GRO J1655–40 seems to show both, hard and soft outbursts within a few weeks.

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