

NASA-TM-111279

NASA REPORT
IN-89
3212
p. 1

Correlations between X-ray outbursts and relativistic ejections in the X-ray transient GRO J1655 - 40

B. A. Harmon^{*}, C. A. Wilson^{*}, S. N. Zhang[†],
W. S. Paciesas[†], G. J. Fishman^{*}, R. M. Hjellming[§],
M. P. Rupen[§], D. M. Scott[‡], M. S. Briggs[†]
& B. C. Rubin[‡]

^{*} ES84 NASA/Marshall Space Flight Center, Huntsville, Alabama 35812, USA

[†] Department of Physics, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA

[‡] Universities Space Research Association, Huntsville, Alabama 35806, USA

[§] National Radio Astronomy Observatory, Socorro, New Mexico 87801-0387, USA

ALTHOUGH objects that emit radio jets have been known for many years, the physical mechanism responsible for the jets has been unclear. Accretion of mass onto a compact object (such as a black hole) has often been invoked in models of their formation¹. X-ray emission from such sources is a potentially powerful probe of the processes taking place, because it seems to arise much closer to the central object. Here we report the detection of X-ray and radio emission from the recently discovered^{2,3} transient source X-ray Nova Scorpii 1994 (GRO J1655 - 40). The radio outbursts, presumably reflecting the feeding of material into relativistic jets, generally follow bursts of hard X-ray emission (20-400 keV) with

a delay that varies from a few days to about two weeks. This suggests that the mechanism behind the X-ray emission is not related to the ejection process in a simple way. Nevertheless, GRO J1655–40 may be the best example of a compact object/accretion-disk system in which models of jet formation and X-ray production can be tested directly.

GRO J1655–40 was first detected on 27 July 1994 with the Burst and Transient Source Experiment (BATSE)⁴ on board the Compton Gamma Ray Observatory (CGRO). The transient source was clearly distinguishable from nearby hard X-ray sources such as OAO 1657–415². The source was located initially to 0.3° uncertainty using Earth occultation imaging⁵. Using additional BATSE data, the uncertainty was reduced³ to ~0.1°, in agreement with the reported optical location⁶.

Figure 1a shows the GRO J1655–40 X-ray lightcurve in the 20–100 keV energy band obtained using the Earth occultation technique. The X-ray lightcurve is dominated by three main outbursts, the first between 28 July and 15 August, the second between 6 and 16 September, and the third which was also the most intense, between 1 November and 25 December. (The third episode could also be considered as two separate, closely spaced outbursts.) The rise in hard X-rays of GRO J1655–40 largely occurred in less than one day, between 27.75 and 28.25 July UT, although there was no well defined maximum during the first outburst. Similarly, the second outburst showed a fast rise on 6 September. There is some evidence for a low-level flux preceding the first and second outbursts, but its significance is marginal, given the combined statistical and systematic error determined for the daily averages in Fig. 1a. The source showed no emission lasting more than 5 d above the level of 0.03 photons cm⁻² s⁻¹ in the 20–100 keV band (~10% of the peak flux) for the 50-day interval before 27 July.

Figure 1b shows the total radio flux at 1.49 GHz measured with the National Radio Astronomy Observatory Very Large Array (VLA). A flux increase in the 1.49 GHz band is associated with each X-ray outburst, but the time of maximum radio flux varies greatly among outbursts: the radio peak for the first outburst occurs about 10 days to 2 weeks after the peak X-ray flux in early August, but in later outbursts, the peak radio flux

appears to follow the X-ray maxima by only 1–2 d. The latter part of the third X-ray outburst in late November and early December, which shows very intense X-ray fluxes, is reflected only as a modest slowing in the decline of the radio flux.

Times when major radio ejection events began are also shown in Fig. 1. These times precede the maximum radio flux by ~1 week and correspond reasonably well to episodes of enhanced X-ray flux, but, as can be seen for the first and third outbursts, not with the peak X-ray flux determined from the daily averages.

To examine these putative relationships in more detail, we have plotted the X-ray and radio data during the first and second X-ray outbursts in Fig. 2 on an expanded scale to illustrate the short-term flux variability of GRO J1655–40. In early August (Fig. 2a), the X-ray source began an overall decline with superimposed shorter timescale variations (hours). Coincident with the X-ray decline, the Australian Molonglo Radio Observatory reported⁷ a rise in flux at 843 MHz from 0.9 to 7.1 Jy. Observations with the VLA, which began on 12 August, also showed an increase in the 1.49, 4.9 and 14.9 GHz bands as shown in Fig. 2a. The radio spectrum, which first exhibited an optically thick, relatively flat spectrum on 12 August, evolved to an optically thin synchrotron spectrum by 18 August.

The second outburst (Fig. 2b) had a slightly more complicated, but similar, behaviour. The 1.49 GHz and 843 MHz radio fluxes showed increases at the times of prominent X-ray dips on 11 and 13–14 September, respectively. Although the radio coverage is less complete than that of the first outburst, the data indicate that the radio spectrum steepens between 11 and 13 September, and possibly continues to steepen until 14 September. Combined Molonglo Observatory and AT Compact Array observations also support a steepening of the radio spectrum⁸. The optically thick spectrum observed by the VLA on 11 September appears to be associated with a new component in the central radio source that is distinct from the extended components seen in the VLA images from the initial outburst⁹.

To search for possible periodic behaviour associated with the short-term X-ray variability, such as a possible binary orbital signature or correlations with the kinematic model being developed for the radio jets⁹, occultation fluxes at 0.1-d intervals were

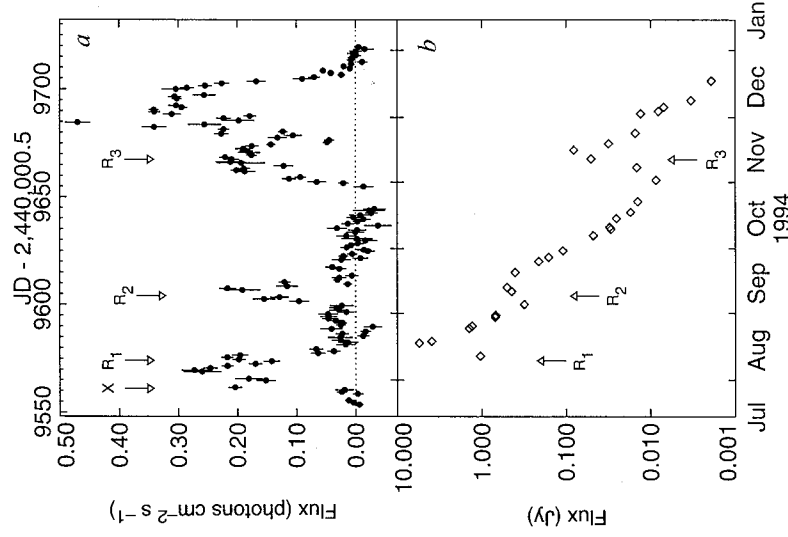


FIG. 1 a, BATSE lightcurve for GRO J1655–40 in the 20–100 keV energy band. Individual occultation measurements are used to compute the daily average fluxes shown. To obtain the photon flux, source count rates are extracted in each energy channel from occultations of the source during a single day (typically ~20 occultations are usable); then, the averaged rates are fit to a power law convolved through the response functions of the BATSE detectors. Other bright sources in the region are accounted for by simultaneously fitting their occultation step features. The indicated errors are statistical; the systematic error is estimated to be 5% of maximum intensity of the first outburst (~0.3 photons cm⁻² s⁻¹, 20–100 keV) due to variability of nearby sources. “X”, “R₁”, “R₂” and “R₃” indicate, respectively, times of the initial rise of the X-ray flux, and the onset of major plasma ejection episodes (jet formation) as determined from VLA images⁹, where R₁ = (truncated Julian date, TJD) 9,574 ± 1 (10 August 1994), R₂ = 9,604 ± 2 (9 September 1994) and R₃ = 9,668 ± 5 (12 November 1994). The jets appear as a semi-continuous stream of radio-emitting plasma with brighter portions which display clear proper motion⁹ corresponding to relativistic velocities at the estimated distance¹² of 3.5 kpc. Some features within the jets can be tracked in separate observations for several days. The times are obtained by extrapolation of the proper motion of the radio-emitting plasma back to the central source⁹. b, 1.49 GHz radio lightcurve for GRO J1655–40 measured with the VLA. The fluxes represent the total intensity of the extended radio source, and are plotted logarithmically to enhance the visibility of secondary features in the lightcurve.

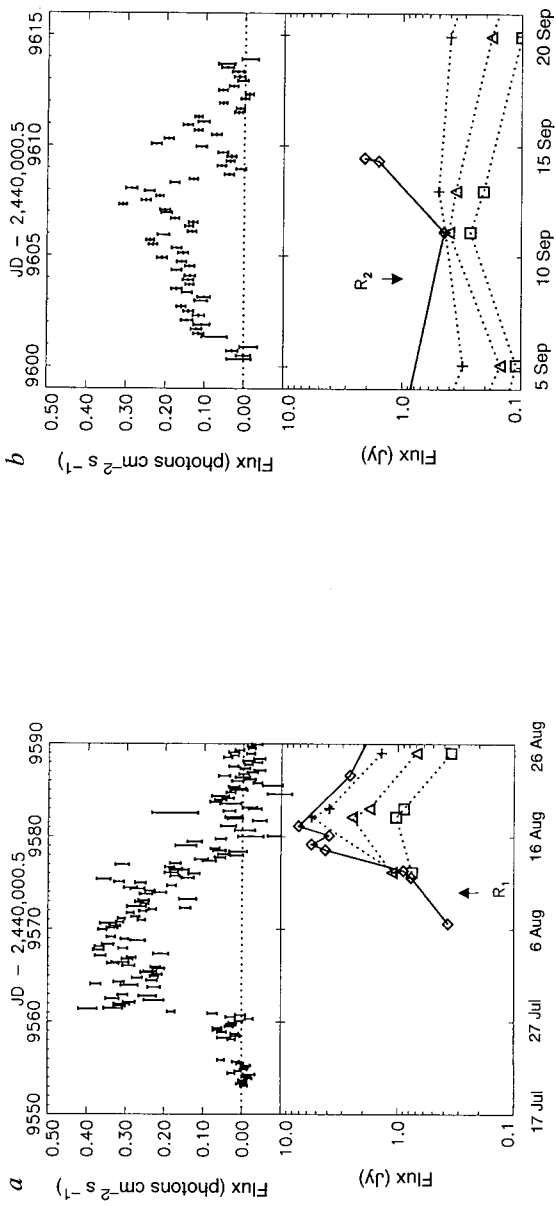


FIG. 2 Lightcurves for GRO J1655-40 in the 20-430 keV band for the first (a) and second (b) outbursts. BATSE occultation data are shown for 0.2-d (4.8-h) sampling intervals which typically include ~ 2 -6 flux measurements. To achieve maximum statistical accuracy, the flux has been calculated from a power-law fit assuming a fixed spectral index of -3.1 and a variable normalization. Simultaneous radio measure-

ments are also shown from the Molonglo observatory at 843 MHz (diamonds) and the VLA at 1.49 (crosses), 4.9 (triangles) and 14.9 GHz (squares). The 843 MHz flux on 11 September (0.45 Jy) is an upper limit based on the optically thick spectrum which peaked^{8,9} at 5 GHz. As described in Fig. 1, R_1 and R_2 indicate the onset of major plasma ejection episodes lasting several days.

processed with a Lomb algorithm for unevenly sampled data¹⁰ to obtain a histogram of periods. This revealed no significant periods between 0.5 and 50 d.

BATSE spectra are shown in Fig. 3 for two time intervals during the first and second outbursts of GRO J1655-40. The spectrum was generally well fitted by a single power law whose photon spectral index showed some evolution during each outburst. The index reached a minimum value of ~ -3.1 , but ranged as high as -2.5 , generally when the intensity was lower; however, no strict hardness-intensity relationship was observed. The spectrum for 4-9 August corresponds to the X-ray peak of the first outburst, which shows no evidence for a cutoff below 400 keV. The Oriented Scintillation Spectrometer Experiment on the CGRO reported¹¹ significant emission between 4 and 9 August up to 600 keV.

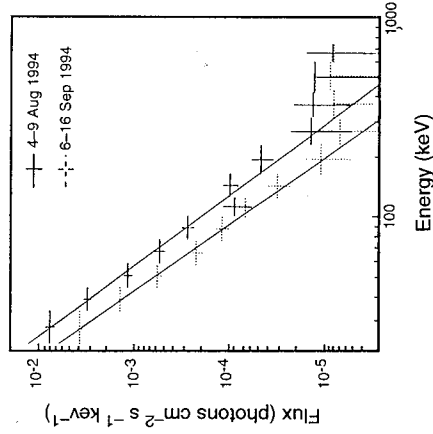


FIG. 3 Energy spectra for GRO J1655-40 from 4 to 9 August (first outburst) and 6 to 16 September (second outburst) 1994. The power-law spectral indices for the fits shown were -2.8 ± 0.06 and -3.0 ± 0.1 for 4-9 August and 6-16 September, respectively. An extrapolation of the spectrum of the first outburst down to 1 keV for a 3.5 kpc source distance¹² yields a luminosity at or exceeding the Eddington luminosity for a $1 M_{\odot}$ black hole.

Based on the estimated¹² distance of 3.5 kpc (lower and upper limits are 3 and 5 kpc, respectively¹³), we derive a 20-100 keV peak luminosity from Fig. 3 of 1.6×10^{37} erg s⁻¹.

GRO J1655-40 seems to be one of a class of objects known as ultra-soft or soft X-ray transients. The more popular, but less accurate, name is X-ray novae. These objects have been shown to be binary systems with a low-mass, late-type main-sequence star and a compact object surrounded by an accretion disk¹⁴. If the companion star is bright enough, Doppler shifts in the visible spectrum signifying the orbital motion of the binary can be observed once the accretion disk returns to its quiescent state. The measured shifts lead to an optical mass function which can be used to set a lower limit on the compact object mass. Three systems have been firmly established to contain a compact object of $3 M_{\odot}$ or larger, and thus are believed to contain black holes¹⁴.

The classification of GRO J1655-40 as an X-ray nova is supported by a variety of observations, mainly the fast rise of the hard X-ray flux, the gradual decline of the radio flux (characteristic of an adiabatically expanding synchrotron radio source), and the appearance of an optical nova with a characteristic low-mass X-ray binary spectrum⁶. Also, multiple secondary radio, optical and X-ray outbursts are frequently seen in such objects¹⁵. However, some of its X-ray and optical properties identify this source as a peculiar X-ray nova, irrespective of its radio properties. Usually secondary outbursts in X-ray novae tend to appear as perturbations on the decline of the main outburst, which is often exponential in shape. This is in stark contrast to the X-ray lightcurve shown in Fig. 1. The early outburst spectrum, as shown in Fig. 3, is also somewhat steeper than the usual spectra of X-ray novae. The optical counterpart of GRO J1655-40 (ref. 6) shows a change in magnitude from quiescence to outburst of $\Delta V \approx 3$ mag, peaking at a visual magnitude of 14.4. More typically¹⁵, $\Delta V \approx 6-7$. Nevertheless, the latter suggests that it will be possible to obtain a mass estimate for the compact object when this system returns to quiescence.

The identification of the compact object in GRO J1655-40 as a neutron star or black hole depends on further studies. In lieu of an optical mass function, we can study the source's high-energy spectral and temporal properties. The detection of pulsations or X-ray bursts would immediately indicate the presence of a neutron star; however, it is not often that these are found

in X-ray novae. Beyond this, there are properties that, taken together, are usually considered to be indicative of 'black-hole systems'¹⁴. They are: (1) an ultra-soft spectrum in the 1–10 keV band, (2) a hard spectral component which extends to several hundred keV, and (3) broad-band, short timescale variability (10^{-3} s), usually when the hard spectral component is present. The TTM-Kvant-Mir team reported an ultra-soft spectrum for GRO J1655–40 on 24 and 25 September with a black-body temperature¹⁶ of 1 keV. Rosat observations¹⁷ show flux variability on timescales down to 0.1 s in the 0.1–1 keV energy band. Although more detailed studies of possible short-timescale variability of the source are underway (D. Cray *et al.*, manuscript in preparation), the standard all-sky monitoring routines performed daily on BATSE background data showed no prominent variability or pulsed emission from the direction of GRO J1655–40 in the time range of 3–300 s at 10% of the peak flux level observed in Fig. 1. The current observational constraints therefore favour the presence of a black hole in GRO J1655–40.

Theoretical arguments indicate that jet-like or collimated supersonic flows can arise from radiation-pressure dominated disks, where mass flow to the inner disk can feed loosely collimated jets of material¹.

A consistent relationship between the hard X-ray and radio fluxes and the plasma ejection times is observed in three distinct episodes of GRO J1655–40. This supports the interpretation that feeding of material into jets occurs in the inner disk, as that is also the most likely site of hard X-ray production. The varying delay times between the X-ray and radio secondary peaks, and the general tendency away from a simple one-to-one relationship between fluxes in the two wavelength bands, indicate that the ejection mechanism is not strictly determined by a critical luminosity as determined from the hard X-ray flux alone. We note that intense soft X-ray fluxes have been detected¹⁶ when the hard X-ray flux as determined by BATSE was relatively weak. Further, we find that the hard X-ray flux shows significant variability on a timescale of hours, and a degree of anti-correlated behaviour with the radio flux, usually after the X-ray flux has reached a maximum. This would suggest that the emission of X-rays and γ -rays is being suppressed by a change of state in the inner disk rather than simply decreasing in response to a reduction in accretion rate.

It is interesting to compare this source with the transient source GRS 1915+105. This object was discovered in August 1992 with GRANAT/WATCH¹⁸ and reported recently by Mirabel and Rodriguez¹⁹ to be a radio source with superluminal jets. Although GRS 1915+105 has a hard X-ray spectrum²⁰ similar to GRO J1655–40, it has not been considered an X-ray nova due to its long risetime²¹. It has undergone long-duration flares since 1992 in hard X-rays²¹ and radio flares up to 1 Jy from 1992 to 1994¹⁹. It is variable over hours to days, and episodes of strong X-ray emission lasting several weeks are interspersed with quiescent periods (K. Deal *et al.*, manuscript in preparation). The dramatic variability of the hard X-rays seen in these two transients would appear to be related to the presence of the radio jets; however, more detailed correlative studies will have to be done. \square

Received 21 October 1994; accepted 10 March 1995.

1. Begelman, M. C., Blandford, R. D. & Rees, M. J. *Rev. mod. Phys.* **58**, 255–351 (1984).
2. Zhang, S. N. *et al.* *IAU Circ. No.* 6046 (1994).
3. Wilson, C. A. *et al.* *IAU Circ. No.* 6056 (1994).
4. Fishman, G. J. *et al.* in *Gamma Ray Observatory Science Workshop* (eds Shrader, C. R., Gehrels, N. & Dennis, B.) 239–250 (CP-3137, NASA, Greenbelt, Maryland, USA, 1989).
5. Zhang, S. N., Fishman, G. J., Harmon, B. A. & Paciesas, W. S. *Nature* **366**, 245–247 (1993).
6. Bally, C. D. *et al.* *Nature* **374**, 701–703 (1995).
7. Campbell-Wilson, D. & Hurstead, R. *IAU Circ. Nos* 6052 & 6055 (1994).
8. Campbell-Wilson, D., McKay, D. J. & Lovell, J. E. *IAU Circ. No.* 6078 (1994).
9. Hjellming, R. M. & Rupen, M. P. *Nature* (submitted).
10. Press, W. H. *et al.* *Numerical Recipes in Fortran 2nd edn* 569–577 (Cambridge Univ. Press, 1992).
11. Kroeger, R. A., Grove, J. E., Kurfess, J. D., Johnson, W. N. & Strickman, M. S. *IAU Circ. No.* 6051 (1994).
12. McKay, D. & Kesteven, M. *IAU Circ. No.* 6062 (1994).
13. In'gday, S. J. *et al.* *Nature* **374**, 141–143 (1995).

14. White, N. E. in *The Evolution of X-ray Binaries* (eds Holl, S. S. & Day, C. S.) 53–60 (AIP Conf. Proc. 308, Am. Inst. Physics, New York, 1994).
15. Van Paradijs, J. & McClintock, J. in *X-Ray Binaries* (eds Lewin, W. H. G. & v. d. Heuvel, E. P. J.) (Cambridge Univ. Press, in the press).
16. Alexandrovich, N., Borozdin, K., Efremov, V. & Sunyaev, R. *IAU Circ. No.* 6087 (1994).
17. Greiner, J. *IAU Circ. No.* 6078 (1994).
18. Sazonov, S. Yu. *et al.* *Astr. Lett.* **20**, 787–791 (1994).
19. Mirabel, I. F. & Rodriguez, L. F. *Nature* **371**, 46–48 (1994).
20. Finoguenov, A. *et al.* *Astrophys. J.* **424**, 940–942 (1994).
21. Harmon, B. A. *et al.* in *The Second Compton Symposium* (eds Fichtel, C. E., Gehrels, N. & Norris, J. P.) 210–219 (AIP Conf. Proc. 304, Am. Inst. Physics, New York, 1993).

ACKNOWLEDGEMENTS. We thank J. van Paradijs for useful comments. The National Radio Astronomy Observatory is operated by Associated Universities Incorporated under a cooperative agreement with the US NSF.