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THE DUAL NATURE OF HARD X-RAY OUTBURSTS FROM THE SUPERLUMINAL X-RAY TRANSIENT SOURCE GRO J1655−40

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ABSTRACT

We report the results of multiwavelength observations of the superluminal X-ray transient GRO J1655−40 during and following the prominent hard X-ray outburst of 1995 March–April. GRO J1655−40 was monitored continuously by BATSE on board the *Compton Gamma Ray Observatory* and observed repeatedly in the radio and optical bands from the ground. About a month after the onset of the hard X-ray outburst, GRO J1655−40 was observed twice by the *Hubble Space Telescope* in 1995 April 25 and 27, with the aim of detecting faint optical emission from ejected plasmoids. Despite the similarity of the hard X-ray emission in 1995 April with previous events in 1994, no radio or optical emission from GRO J1655−40 related to plasmoids was detected. We conclude that GRO J1655−40 is subject to complex behavior showing radio-loud hard X-ray outbursts with strong radio emission (of flux $f_r \gtrsim 100$ mJy), both from a "core" source and from propagating plasmoids (as those in 1994), and radio-quiet hard X-ray outbursts with no detectable radio emission and plasmoid activity ($f_r \lesssim 0.5$ mJy) (as those in 1995). Our results can constrain models of particle acceleration and radiation of relativistic plasmoids.

Subject headings: acceleration of particles — instabilities — MHD — radiation mechanisms: nonthermal — radio continuum: stars — X-rays: stars

1. INTRODUCTION

Superluminal X-ray transients form a newly discovered class of Galactic sources showing strong hard X-ray outbursts and sporadic relativistic ejection of radio-emitting plasmoids in a double-jet geometry. Qualitatively, the jet geometry of superluminal X-ray transients resembles that of active galactic nuclei and SS 433, suggesting similar conditions of accretion onto their respective compact objects. Two clearly established superluminal transients are currently known in the Galaxy: GRS 1915+105 (Mirabel & Rodriguez 1994) and GRO J1655−40 (Harmon et al. 1995, hereafter H95; Hjellming & Rupen 1995, hereafter HR95; Tingay et al. 1995, hereafter T95).

GRO J1655−40 (Nova Scorpii 1994) was discovered at the end of 1994 July by the Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma Ray Observatory* (*CGRO*) near the Galactic plane (Zhang et al. 1994). The distance derived from the jet kinematics of 3.5 kpc (HR95) is supported by the measurements of the 21 cm H I (McKay & Kesteven 1994; T95), X-ray absorption (Inoue et al. 1994), and optical absorption (Horne et al. 1996).

GRO J1655−40 exhibited three prominent hard X-ray outbursts during 1994 (H95) (approximate starting dates: 1994 July 31, September 6, November 10). In all of these outbursts, GRO J1655−40 showed remarkable radio flaring in the gigahertz range during or immediately following episodes of intense hard X-ray emission (H95; T95; HR95). For these outbursts, superluminal motion of radio plasmoids was repeatedly observed (HR95). From VLA and VLBA maps obtained during the period of 1994 August–November, it was possible to deduce a time-variable geometry of plasmoid ejection in oppositely directed jets (HR95) resembling the precessing jets of SS 433 (e.g., Margon 1984). A kinematic model for the major plasmoid ejections and propagation in 1994 gives a plasmoid velocity $\beta_p = v/c = 0.92 \pm 0.02$, and an angle between the radio jet axis and the line-of-sight direction, $i \sim 85°$ (HR95).

Optical photometry obtained after the first hard X-ray outburst in 1994 August revealed a brightened optical counterpart with a visual magnitude in the range $V \sim 14$–16 and a change from the quiescent magnitude $V_q \sim 17.3$ (Bailyn et al. 1995, hereafter B95a). The red color of the optical counterpart with $E(B-V) = +1.3 \pm 0.2$, as recently determined by deep 200 nm *Hubble Space Telescope* (*HST*) observations in 1995 May (Horne et al. 1996), indicates significant absorption in the direction of GRO J1655−40 (see also B95a). Spectroscopic CTIO observations of GRO J1655−40 carried out in early 1995 May revealed Doppler-shifted high-excitation emission lines superposed on an F-type or early G-type stellar absorption spectrum (Bailyn et al. 1995b, hereafter B95b). If the result of a companion star, the line-velocity profile indicates an orbital period $P_{\rm opt} = 2.62 \pm 0.03$ days and an inferred mass function $f(M_2) = 3.16 \pm 0.15\ M_\odot$ (B95b). A large mass function, together with the constraints on the mass of the companion star, favors an interpretation of GRO J1655−40 in terms of a black hole system of primary mass $m \gtrsim 3\ M_\odot$ (B95b; see also Zhang et al. 1996).

Motivated by the apparent repetitive behavior of GRO J1655−40 during the 1994 August–1995 January outbursts (hard X-ray emission, strong radio emission, plasmoid propagation with associated radio emission lasting for several

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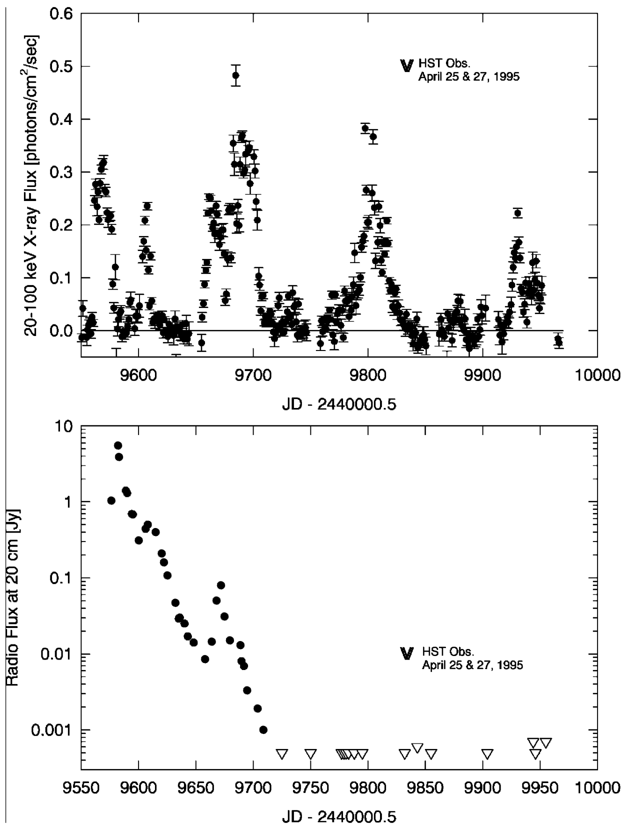

FIG. 1.—Combined 1 day–averaged BATSE (20–100 keV) (*upper plot*) and VLA (*lower plot*) light curves of GRO J1655−40 covering the time period 1994 August–1995 August. VLA data points (1.49 GHz) are marked with filled circles, and upper limits (4.9/8.4 GHz) are marked with open triangles. The 1995 March–April hard X-ray outburst is clearly evident, together with the absence of detectable radio emission since late 1994 December. The dates of the *HST* observations of GRO J1655−40 (1995 April 25 and 27) are marked as downward-pointing arrows in both plots.

weeks), we planned a series of multiwavelength observations. The previous activity of GRO J1655−40 in 1994, which showed a recurrent 2–3 week delay between the hard X-ray emission onset and the peak radio emission and plasmoid propagation (H95; HR95), allowed us to plan an observational campaign extending in time for about 1 month.

The opportunity for activating the planned campaign was offered in 1995 March, when BATSE detected a strong hard X-ray outburst of GRO J1655−40 with characteristics very similar to the previous ones (Wilson et al. 1995). The subsequent weeks of activity of the source coincided with previously scheduled ground-based optical and radio observations. Furthermore, a target of opportunity *HST* observation was granted and scheduled within ∼1 month of the hard X-ray outburst onset.

2. OBSERVATIONS

2.1. *BATSE*

BATSE can continuously monitor hard X-ray sources in the 20 keV–2 MeV band by the Earth occultation technique (Harmon et al. 1992). BATSE effectively monitored hard X-ray emission of GRO J1655−40 since its discovery in late 1994 July (H95). Figure 1 shows the BATSE (1 day–averaged) light curve of hard X-ray emission in the 20–100 keV band extending up to 1995 August. A prominent hard X-ray outburst was detected during the period 1995 March–April (∼MJD 9770–9820), with peak flux corresponding to ∼1.3 Crab units around 1995 March 24 (MJD 9800). Both the rise and the decay parts of the light curve have similar characteristics, and the whole hard X-ray outburst has a "triangular" shape.

2.2. *Radio Observations*

Radio observations of GRO J1655−40 were carried out at the Very Large Array (VLA)[7] throughout the whole period of the continuous BATSE monitoring. The 1995 observations were made at 4.9 and 8.4 GHz, and in all cases no radio emission was detected with an upper limit of 0.5 mJy. Figure 1 shows the complete (logarithmic) 1994–1995 VLA radio light curve of GRO J1655−40 at 1.49 GHz for 1994 and the 4.9/8.4 GHz upper limits in 1995, plotted on the same temporal scale as the BATSE data. The prominent 1994 radio flares of GRO J1655−40, coincident with the hard X-ray outbursts, are clearly evident (H95; HR95). The last VLA radio detection of GRO J1655−40 occurred in 1994 near mid-December, coincident with the final decay of the 1994 November–December hard X-ray outburst. Since then, the radio source was not detected again until the recent flare[8] in 1996 (Hunstead & Campbell-Wilson 1996; Hjellming & Rupen 1996).

The diversity of the radio/hard X-ray correlation between the 1994 and the 1995 behavior of the source is evident from Figure 1. Contrary to previous activity in 1994, the 1995 March–April (and 1995 mid-August) hard X-ray outbursts were not followed by detectable radio flaring. In particular, there was no detectable radio emission at the time of the *HST* observations, as indicated by the vertical lines superposed on the radio light curve in Figure 1. What may be a third class of behavior was seen for the 1996 flare event.

2.3. *HST Observations*

Following the 1994 activity of GRO J1655−40, *HST* observations aimed at detecting optical emission from plasmoids were proposed. The relative proximity of the radio plasmoids to the central source after 1–2 weeks of propagation as observed in 1994 ($0''.3$–$0''.4$; HR95; T95), the brightness of the central source (B95a; B95b), and the faintness of the estimated optical emission of plasmoids all require the superior imaging capability of the refurbished *HST*.

Target of opportunity *HST* Wide Field Planetary Camera 2 (WFPC2) observations of GRO J1655−40 were carried out on 1995 April 25 and 27. A red filter (F675W) was chosen to maximize the possibility of detection given the extinction along the direction of the source. Two visits, separated by approximately 48 hr, were planned, in order to determine the velocity of any ejecta that might be detected. On each visit, we obtained four 40 s exposures in each of the four positions, using the PC camera of the *HST* WFPC2. The four positions

[7] The VLA is a facility of the NRAO, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[8] The 1996 X-ray flare was detected by the *Rossi X-Ray Timing Explorer's* all-sky monitor (ASM) (Remillard et al. 1996) on 1996 April 25. Horne et al. (1996) reported the optical/ultraviolet brightening of GRO J1655−40 on May 10. VLA upper limits for the detection of radio emission from this object were obtained after the onset of the X-ray flare on May 10, 12, and 20. With the Hunstead & Campbell-Wilson (1996) detection of 55 mJy at 843 MHz on May 28 and the Hjellming & Rupen (1996) detection of 19 mJy at 4.9 GHz on May 29, the onset of the radio flare must have been between 24 and 32 days after the beginning of the X-ray outburst detected by the ASM. A detailed account of the 1996 emission event will be presented elsewhere.

TABLE 1

1995 April *HST* Observations of GRO J1655−40

d (1)	f_0/f_c (2)	R_C (3)	R'_C (4)	$f(R'_C)$ (5)	$L(R'_C)$ (6)
0$''$.2…….	0.03	19.9	16.6	7.4×10^{-13}	1.1×10^{33}
0$''$.5…….	0.002	22.8	19.5	5.1×10^{-14}	7.4×10^{31}
0$''$.7…….	0.0005	24.3	21.1	1.3×10^{-14}	1.9×10^{31}

Notes.—Col. (1): angular distance from the central source (in arcseconds); col. (2): ratio of the R_C-band energy flux upper limit at the distance d to the flux from the central source; col. (3): apparent R_C magnitude upper limits of plasmoids at the distance d (not corrected for extinction); col. (4): true R_C magnitude upper limits of plasmoids corrected for extinction; col. (5): upper limit to the energy flux (in ergs cm^{-2} s^{-1}) corresponding to the R'_C magnitude; col. (6): upper limit to the optical luminosity (in ergs s^{-1}) corresponding to the R'_C magnitude for a source at 3.5 kpc.

were placed on a parallelogram, whose vertices were offset by nonintegral pixel shifts. These positions fully sampled the instrumental point-spread function (PSF). In addition, on the second visit, the telescope was rolled by approximately 25° with respect to the orientation of the first visit. Rolling the telescope causes any nonaxisymmetric features of the PSF to rotate with respect to the sky, and thus it simplifies the task of distinguishing between faint PSF artifacts and astrophysical emission.

The four images at each dither position were then cleaned of cosmic rays and averaged. The four resulting images from each visit were finally combined by shifting and adding. Figure 2 (Plate L15) shows the image obtained during the first 1995 April 25 visit (source position: R.A. = $16^h54^m00^s.137$, decl. = −39°50′44$''$.90 ± 0$''$.20 (equinox J2000). The central source has a Cousins average apparent magnitude (bandpass 0.57–0.72 μm) of $R_C = 16.22 \pm 0.03$ in the first visit and $R_C = 15.97 \pm 0.03$ for the April 27 visit. No sign of additional optical emission, other than that of the central point source, was immediately obvious in either image. As a further check, the subsampled images were scaled and subtracted from one another. The difference image was then deconvolved with the PSF, and the residuals measured. No emission of flux higher than 0.03 times that of the star was found within 0$''$.2 of the stellar position. The limit within 0$''$.5 is ∼0.002, and beyond 0$''$.7, the limit is ∼0.0005 times that of the stellar flux. The apparent R_C magnitude upper limits to plasmoid optical emission are in the range $20 \lesssim R_C \lesssim 24$. The apparent R_C magnitudes need to be corrected for extinction, and the corrected upper limits are $R'_C = R_C - A_{R_C}$, with $A_{R_C} = 3.25$ [assuming $E(B-V) = 1.3$]. Table 1 summarizes the relevant *HST* upper limits to optical emission of plasmoids from GRO J1655−40 in late 1995 April.

3. DISCUSSION

Our observations can constrain models of particle acceleration and radiation of the relativistic plasmoids of GRO J1655−40. The particle composition and the energy spectrum of particles in the plasmoids are unknown. The only established fact is the radio emission in the 10^9–10^{10} Hz frequency range as observed in 1994 (HR95; T95). This radio emission implies a relativistic Lorentz factor for the radiating electrons/positrons at the distance r', $\gamma_{e,r} \sim 7.5\nu_9^{1/2}B(r')^{-1/2}$, where ν_9 is the photon frequency in units of 10^9 Hz and $B(r')$ is the local magnetic field in gauss (e.g., Pacholczyk 1969). A single distribution of particle energies $N(\gamma_e) \propto \gamma_e^{-\delta}$ with $\gamma_{\min} \le \gamma_e \le \gamma_{\max}$ may produce (self-Compton) synchrotron radiation in the optical band for a variety of conditions, including adiabatic expansion and radiation [shock reenergization along the jet may produce an effective $N(\gamma_e)$ more complex than a single power law]. If the Lorentz factor of the optically radiating particles γ_o satisfies the relation $\gamma_{\min} \le \gamma_{e,r} \ll \gamma_o \le \gamma_{\max}$, with $\gamma_o \sim 300\gamma_{e,r}$, synchrotron radiation may occur from the radio to optical band as observed in several extragalactic jet sources (e.g., M87; Biretta et al. 1993). We call this model of emission model 1. Alternately, the low-energy cutoff of $N(\gamma_e)$ may be shifted occasionally at higher energies, with $\gamma_{\min} > \gamma_{e,r}$, or synchrotron self-absorption can occur. In this case, a "radio-invisible" plasmoid can be produced, and depending on the ratio of $\gamma_{\min}/\gamma_o$ and on the self-absorption frequency, optical emission may still be detectable. We call this model of emission model 2. Deep optical observations of propagating plasmoids of Galactic superluminal transients can, in principle, constrain $N(\gamma_e)$ and its range.

A synchrotron model of emission assumes a plasmoid containing relativistic electrons (and positrons, if present) plus baryons being ejected with a bulk velocity β_p and subject to radiative and adiabatic losses. The radiating particles are likely to be impulsively accelerated by a shock or by a MHD acceleration mechanism in a way similar to that proposed for jets of extragalactic sources and young stellar objects (e.g., Blandford 1993; Königl 1989). After an initial phase dominated by optically thick emission, the synchrotron emission model leads, in general, to a broken power-law emission extending from radio to higher frequencies. The observed slope of the 1994 radio emissivity (in the frequency range 10^9–10^{10} Hz) from the plasmoids of GRO J1655−40 is $\alpha_0 \sim 0.4$–0.6 (HR95). The spectral slope may change because of synchrotron losses to $\alpha_0 + \frac{1}{2}$ at a "break frequency" ν_b that depends on the magnitude of the magnetic field convected by the plasmoid along the jet (e.g., Königl 1981). The observed[9] radio luminosity near 10^9 Hz of an individual plasmoid ejected from GRO J1655−40 is $L_r \sim 10^{31} f_J$ ergs s^{-1}, where f_J is the radio flux (in janskys). Observations of radio flares of GRO J1655−40 show that $f_J \sim 1$ for the early part of major plasmoid ejections in 1994 (HR95). One can then calculate the expected optical luminosity of GRO J1655−40 plasmoids for a variety of acceleration and emission characteristics. For simplicity, we consider here only the general properties of the synchrotron emission model. In principle, optical emission from plasmoids can also be produced by a synchro-Compton mechanism or by internal or external shocks generating continuum and line emission. A systematic discussion of optical emission mechanisms of Galactic transient plasmoids will appear elsewhere.

The radio spectra of the 1994 plasmoids suggest an energy index $\delta \sim 2$. The optical luminosity in the R_C band, $L_o(R_C)$ from the synchrotron mechanism, can therefore be estimated as $L_o/L_r \gtrsim 200$, for $\nu_b > 10^{14}$ Hz. If plasmoids were produced as in the 1994 flares with $f_J \sim 1$, optical emission in the R_C band would have been detectable by our *HST* observations for an estimated observable luminosity $L_o \sim 3 \times 10^{33}$ ergs s^{-1}. For lower radio emission, a synchrotron model with $\nu_b > 10^{14}$ Hz and $\delta = 2$ can be tested by two-visit *HST* observations for plasmoids emitting radio emission of flux $f_J \gtrsim 0.1$ within 0$''$.5 of the central source, and for $f_J \gtrsim 0.01$ within an angular

[9] The true luminosity L_t for jet-related emission toward the Earth is related to the apparent luminosity by $L_t = (1-\xi)L_r/b$, where ξ is the fraction of radio luminosity produced by the core source and by the counterjet, and $b = [(1-\beta_p^2)^{1/2}(1-\cos i)^{-1}]^{3+\alpha_0}$.

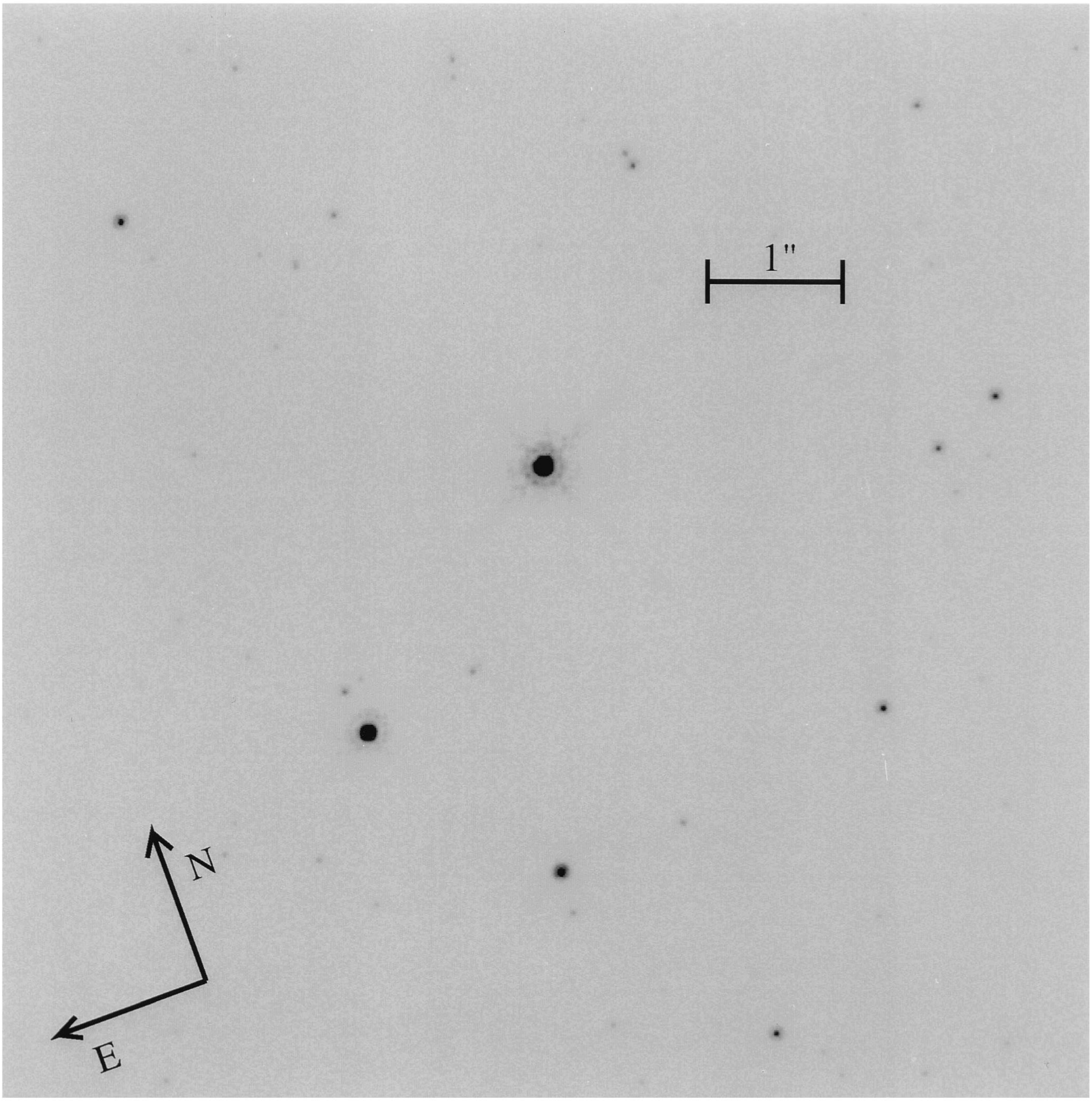

FIG. 2.—*HST* WFPC2 image (F675W filter) of GRO J1655−40 and its surrounding field obtained on 1995 April 25. GRO J1655−40 is the brightest source, slightly displaced from the center of the image. Only the central source of apparent R_C magnitude 16.2 is detected.

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distance of 1″ (see Table 1). This optical emission is expected to be simultaneous with the appearance of a peaking radio flare from the optically thin jet.

The lack of detected radio plasmoids during our two-visit *HST* observations does not allow the testing[10] of model 1. However, model 2 can be constrained by our observations, with the assumption of a plasmoid fractional energy available to radiation similar to the 1994 episodes, for $\gamma_{\min} \sim \gamma_o$ and $L_o \sim 3 \times 10^{33}$ ergs s^{-1}. We find that the total energy of the possibly radio-invisible plasmoids of GRO J1655−40 in 1995 March–April is constrained to be less by approximately 2 orders of magnitude compared with the first 1994 August event.

4. CONCLUSIONS

The behavior of GRO J1655−40 can be remarkably dissimilar for different hard X-ray outbursts. For the first time in a Galactic superluminal transient, the lack of detectable radio and plasmoid emission in 1995 April establishes the "dual" nature, which is probably of the accretion process, producing the hard X-ray outbursts. We can therefore establish the existence of two kinds of hard X-ray outbursts for GRO J1655−40:

1. Radio-loud hard X-ray outbursts, as those characterized by major radio flares of the central source and associated plasmoid propagation detected in 1994. The radio luminosity (core plus plasmoid) was observed to be in the range 10^{29} ergs s^{-1} $\lesssim L_r \lesssim 10^{32}$ ergs s^{-1} for a source at a 3.5 kpc distance. The ratio η_R of radio to hard X-ray luminosities of radio-loud events is therefore $10^{-8}/b \lesssim \eta_R \lesssim 10^{-5}/b$, with b the beaming factor defined above ($b \sim 0.05$ for the jet directed toward the Earth).
2. Radio-quiet hard X-ray outbursts, as those observed in 1995 and characterized by the absence of detectable radio emission with a ratio η_Q of radio to hard X-ray luminosities satisfying the relation $\eta_Q \lesssim 10^{-9}/b$. No optical emission down to $R'_C \sim 20$ is detected at $\sim 0\farcs5$ from the central source, making the existence of "radio-invisible" jets implausible.

The upper limit on radio emission for the radio-quiet hard X-ray outbursts of GRO J1655−40 is about 3 orders of magnitude smaller than the brightest emission of radio-loud outbursts. It is then clear that the accretion processes leading to strong hard X-ray emission are not uniquely related to relativistic plasmoid energization and outward propagation. Hard X-ray emission was always detected preceding the 1994 major radio flares of GRO J1655−40 (H95; HR95). However, similar hard X-ray outbursts of GRO J1655−40 can have a very different behavior in the radio band, as shown by the 1995 activity. It is interesting to note that a somewhat similar behavior was found in the broad-line radio galaxy 3C 390.3. In a recent paper, Eracleous, Halpern, & Livio (1996) have shown that the ejection of radio blobs in this object does not appear to be correlated with any fluctuation of the X-ray flux in the 1–10 keV band. This could mean that the ejection of plasmoids responds more to instabilities in the plasma outflow or corona rather than to changes in the accretion rate.

We also note that possibly elongated near-IR emission was detected in 1995 July from the superluminal jet source GRS 1915+105 (Sams, Eckart, & Sunyaev 1996). If the result of jets, this near-IR emission might indicate the existence of an energetic population of particles in the plasmoids. Simultaneous radio observations of GRS 1915+105 (Foster et al. 1996) show a low-intensity flux (at 2–8 GHz) well below a simple power-law extrapolation from IR to radio bands. We deduce that the elongated IR emission from GRS 1915+105 was due to either the synchrotron jet emission strongly absorbed in the radio band or the interaction with the environment of radio-invisible jets. Our 1995 April observations exclude both these possibilities for GRO J1655−40.

The exceptional nature of GRO J1655−40 stimulated an unprecedented coverage of its X-ray and radio emission during an extended period of time. Future observations will determine whether the dual outbursting behavior of GRO J1655−40 is the norm or the exception among the superluminal transients and black hole candidates.

[10] Table 1 shows that an improvement in flux sensitivity by 2 orders of magnitude would be necessary to constrain model 1 for $f_J \sim 0.0005$ corresponding to the VLA upper limit of 0.5 mJy.

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