THE ASTROPHYSICAL JOURNAL, 472:L111–L114, 1996 December 1

INFRARED OBSERVATIONS OF AN ENERGETIC OUTBURST IN GRS 1915+105

I. F. MIRABEL,[1,2] L. F. RODRÍGUEZ,[3] S. CHATY,[1] M. SAUVAGE,[1] E. GERARD,[4] P.-A. DUC,[5] A. CASTRO-TIRADO,[6] AND P. CALLANAN[7]

Received 1996 July 5; accepted 1996 September 13

ABSTRACT

In the course of an intense X-ray and radio outburst of GRS 1915+105, we observed a pair of radio-emitting clouds emerging from the compact core in opposite directions at relativistic speeds. At near-infrared wavelengths we observed the time-delayed reverberation of this radio flare/ejection event. Five days after the radio outburst, the source became redder as it brightened by ~1 mag in K(2.2 μm), which suggests the appearance of a warm dust component. The enhanced infrared emission was close to 10% of the X-ray luminosity of the source and amounts to about 0.1% of the typical kinetic energy in the bulk motion of the relativistic ejecta in GRS 1915+105.

Subject headings: infrared: stars — radio continuum: stars — stars: individual (GRS 1915+105) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

During the year 1994, Rodríguez & Mirabel (1996) observed repeated relativistic ejections of twin pairs of plasma clouds in the galactic superluminal source GRS 1915+105 (Mirabel & Rodríguez 1994). In the course of a multiwavelength study of this source carried out in 1995 August, we observed with the Very Large Array a relativistic ejection associated to the most prominent X-ray/radio outburst of that year (Sazonov, Sunyaev, & Lund 1996; Harmon, Paciesas, & Fishman 1995; Foster et al. 1996). Besides radio observations at $\lambda = 3.5$ cm with the VLA in the A configuration, and at $\lambda = 9$ cm and $\lambda = 20$ cm with the Nançay radiotelescopes, we have followed this major outburst in the J(1.25 μm), H(1.65 μm), and K(2.2 μm) bands using different infrared facilities. The infrared observations were aimed to study the long-term variability of the stellar counterpart of GRS 1915+105 (Mirabel et al. 1994) as well as the relationship of the infrared emission to the radio and X-ray emission.

The time delay of the infrared response to this major radio flare/ejection event, together with the reddening of the source, provide evidences for thermal reradiation from heated dust. From the infrared lag due to the light crossing time and the enhancement of the infrared luminosity in the H and K bands, we infer the mass of warm dust and its distance from GRS 1915+105. We compute the energy radiated in the infrared and compare it with the X-ray and kinetic power of GRS 1915+105.

2. THE RADIO, INFRARED, AND X-RAY OUTBURST

In Table 1 are listed the integrated radio flux densities of GRS 1915+105 measured with the Nançay and VLA radiotelescopes during a period of 1 month around a strong radio flare on 1995 August reported first by Gihgo, Waltman, & Foster (1995). In Figure 1*a* are plotted the fluxes listed in Table 1. The radio light curves show a large rise in the radio flux in less than 3 days. In fact, Foster et al. (1996) report that the rise from a low-intensity plateau to maximum flare took place between TJD 9938.1 and TJD 9938.9, namely, in ≤18 hours.

The light curve in Figure 1*a* also shows a rapid drop of the flux. At $\lambda = 21$ cm it decreased by 60% in 24 hours. The radio light curve of GRS 1915+105 for the period 1993 December to 1994 April by Rodríguez et al. (1995) revealed the existence of outbursts with this type of time evolution. For instance, a flare on 1993 December 11 showed at $\lambda = 21$ cm a drop in intensity by 45% in 24 hours. These short-lived flares are unlike the long-lasting radio outbursts such as the one on 1994 March–April, which Mirabel & Rodríguez (1994) followed for several weeks with the VLA.

In Table 2 are listed the J(1.25 μm), H(1.65 μm), and K(2.2 μm) magnitudes of GRS 1915+105 at epochs close to the 1995 August 10 outburst. The magnitudes for the four epochs of 1995 August were derived by us from broadband images using relative photometry with nearby stars, and applying particular care in removing from low-resolution images the confusion from a star nearby to GRS 1915+105. The data reduction techniques and calibration procedures are described by Chaty et al. (1996). The K magnitude on 1995 September 4 was estimated using the $2\farcs46$ slit UKIRT spectrum by

TABLE 1

RADIO OBSERVATIONS OF GRS 1915+105

			FLUX DENSITY (mJy)		
			VLA	Nançay	
DATE	UT (hr)	TJD[a]	$\lambda = 3.5$ cm	$\lambda = 9$ cm	$\lambda = 21$ cm
1995 Jul 26......	21.0	9924.9	...	90	...
1995 Jul 29......	21.0	9927.9	...	70	...
1995 Jul 31......	...	9929	1.2	...	...
1995 Aug 07	21.0	9936.9	...	75	...
1995 Aug 10	...	9939	423.0	...	...
1995 Aug 10	21.0	9939.9	...	390	610
1995 Aug 11	21.0	9940.9	...	130	250
1995 Aug 12	21.0	9941.9	...	110	180
1995 Aug 13	21.0	9942.9	...	50	70
1995 Aug 14	21.0	9943.9	...	60	50
1995 Aug 17	...	9946	3.1	...	...
1995 Aug 24	...	9953	0.1	...	...

[a] Truncated Julian Date (JD − 2,440,000.5).

---

[1] Service d'Astrophysique/CEA, DSM/DAPNIA, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette, France.

[2] Instituto de Astronomía y Física del Espacio, Argentina.

[3] Instituto de Astronomía, UNAM, Apdo. Postal 70-264, 04510 México, D.F., Mexico.

[4] Dept. ARPEGES, Observatoire de Paris, Section de Meudon, 5 Place Jules Janssen, 92195 Meudon, France.

[5] European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching-bei-München, Germany.

[6] Laboratorio de Astrofísica Espacial y Física Espacial, INTA, P.O. Box 50727, E-28080 Madrid, Spain.

[7] Smithsonian Astrophysics Observatory, 60 Garden Street, Cambridge, MA 02138.

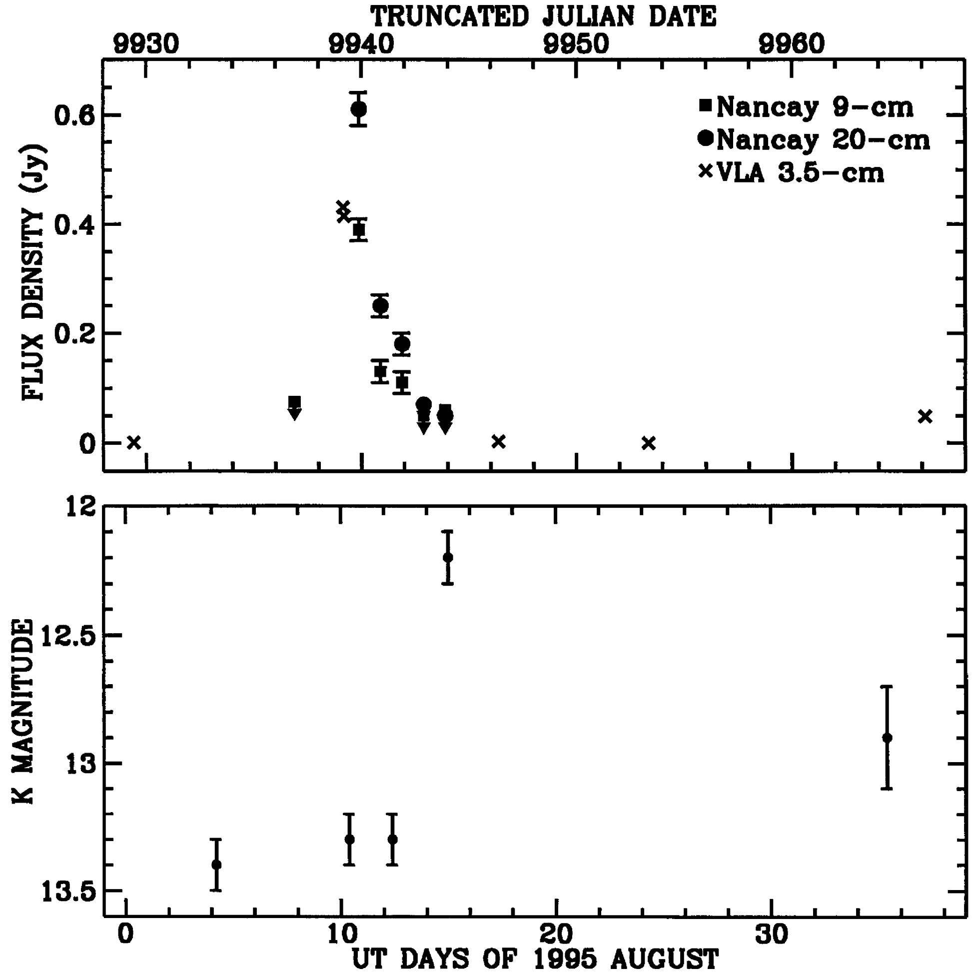

FIG. 1.—(*a*) Radio observations of GRS 1915+105 around the 1995 August outburst/ejection event as observed with the VLA at λ = 3.5 cm, and with the Nançay radiotelescope at λ = 9 cm and λ = 20 cm. (*b*) Infrared K(2.2 μm) magnitudes of GRS 1915+105. Note the time delay of the infrared brightening relative to the time of peak radio emission. TJD = JD − 2,440,000.5.

Mirabel et al. (1996), whereas those of 1995 October are the magnitudes as reported by Eikenberry & Fazio (1995).

The infrared reverberation of the radio flare/ejection that is shown in the K-band light curve of Figure 1*b* had a time delay in the range of 2–5 days relative to the peak radio emission. Table 2 shows that the J and K magnitudes on August 10 and August 12 (TJD 9939.4 and TJD 9941.4), obtained respectively 10 hr and 60 hr after the peak radio emission (Foster et al. 1996), showed no significant change (see Table 2). However, on August 15, 5 days after the maximum in radio, we found that GRS 1915+105 had brightened by 1.1 mag in K and by 0.8 mag in H, but no significant change was observed in the J band (see Table 2). Three weeks later, the source was observed fading in K, and in 1995 October, it had returned to the preburst magnitudes observed in early August.

In the X-rays, the outburst was followed by *GRANAT*/WATCH in the 8–20 and 20–60 keV bands (Sazonov et al. 1996), and by BATSE in the 20–100 keV energy band (Foster et al. 1996). After 4 days of more or less steady emission in the 20–100 keV band, on 1995 August 10 the radio

TABLE 2

INFRARED MAGNITUDES OF GRS 1915+105

Date	UT (hr)	TJD[a]	J (1.25 μm)	H (1.65 μm)	K (2.2 μm)	Telescope	Reference
1995 Aug 4..........	5.0	9933.2	17.8 ± 0.1	···	13.4 ± 0.1	ESO 2.2 m	
1995 Aug 10.........	9.5	9939.4	17.6 ± 0.1	14.9 ± 0.1	13.3 ± 0.1	UKIRT 3.8 m	
1995 Aug 12.........	9.4	9941.4	17.6 ± 0.1	···	13.3 ± 0.1	Lick 3 m	
1995 Aug 15.........	0.0	9944.0	17.7 ± 0.1	13.7 ± 0.1	12.2 ± 0.1	ESO 2.2 m	
1995 Sep 04.........	8.7	9964.4	···	···	≥12.9 ± 0.1	UKIRT 3.8 m	1
1995 Oct 16.........	0.1	10006.0	···	14.9 ± 0.1	13.5 ± 0.1	Kitt Peak 2.1 m	2
1995 Oct 17.........	0.1	10007.0	17.8 ± 0.2	15.2 ± 0.1	13.4 ± 0.1	Kitt Peak 2.1 m	2

[a] Truncated Julian Date (JD − 2,440,000.5).

References.—(1) Mirabel et al. 1996; (2) Eikenberry & Fazio 1995.

flux was observed peaking at the beginning of a sudden drop of the hard X-rays (Foster et al. 1996). A correlation between the hard X-rays and radio fluxes was also observed at the time of the 1994 March–April outburst-ejection event (Harmon et al. 1996).

3. A RELATIVISTIC EJECTION

The major outburst of 1995 August took place at a time when the VLA was in the A configuration, providing the instrument's higher angular resolution. The array remained in this configuration until early 1995 September. For an interval of 3 weeks we were able to follow the large proper motions of a pair of bright radio condensations emerging in opposite directions from the compact radio core.

Figure 2 shows maps of GRS 1915+105 at $\lambda = 3.5$ cm for three epochs 1 week apart. On August 10, at the time of a peak radio emission of 431 mJy the source was unresolved. On August 17 when we measured a flux density of 3.1 mJy it exhibited an elongated structure, and on August 24 two distinct condensations became apparent. The angular resolution of the observations was 0.″2, and the positions were determined by absolute astrometry with accuracies of 0.″02.

Because of the rapid drop of the radio flux, the errors in the kinematic parameters of the ejecta for 1995 August are relatively large. Using Gaussian fits, on 1995 August 24 we measured flux densities of 0.12 ± 0.02 mJy and 0.13 ± 0.02 mJy from the southern and northern condensations, respectively, with angular distances from the radio core source of 0.″16 ± 0.″03 and 0.″12 ± 0.″03 arcsec, respectively, along a position angle of 140° ± 10°. Assuming that the ejection took place on 1995 August 10, the south component moved at 11 ± 2 mas day^{-1} and the north component at 9 ± 2 mas day^{-1}.

When compared with the four relativistic ejections followed by Rodríguez & Mirabel (1996) in 1994 January–June, we find that in 1995 August the position angle for the direction of motion was the same within the errors, but the southern ejecta appeared to be moving slower (compared with 17.6 ± 0.4 mas day^{-1}), whereas the northern ejecta appeared to move, within the errors, at the same speed. Furthermore, the south and north components 2 weeks after the ejection event in 1995 August had equal brightness, whereas in the 1994 January–June observations, 2 weeks after ejections, the fluxes of the southern components appeared to be about 3 times brighter than the northern component. This reduction in the transverse apparent velocities and observed flux ratios from 1994 to 1995 could be due to a change of the direction of the jets toward the plane of the sky, to a change in the actual speed of the jets, or to a combination of both.

4. DISCUSSION

4.1. *Origin of the Near-Infrared Enhancement*

Because the infrared brightening had a time delay in the range of 2–5 days relative to the sudden radio flare/ejection event, the agent of the infrared response to this impulsive event must be at ≥2 light-days from the compact object. Therefore, the infrared response did not come from the cooler component of an accretion disk with a typical size of a few light-seconds.

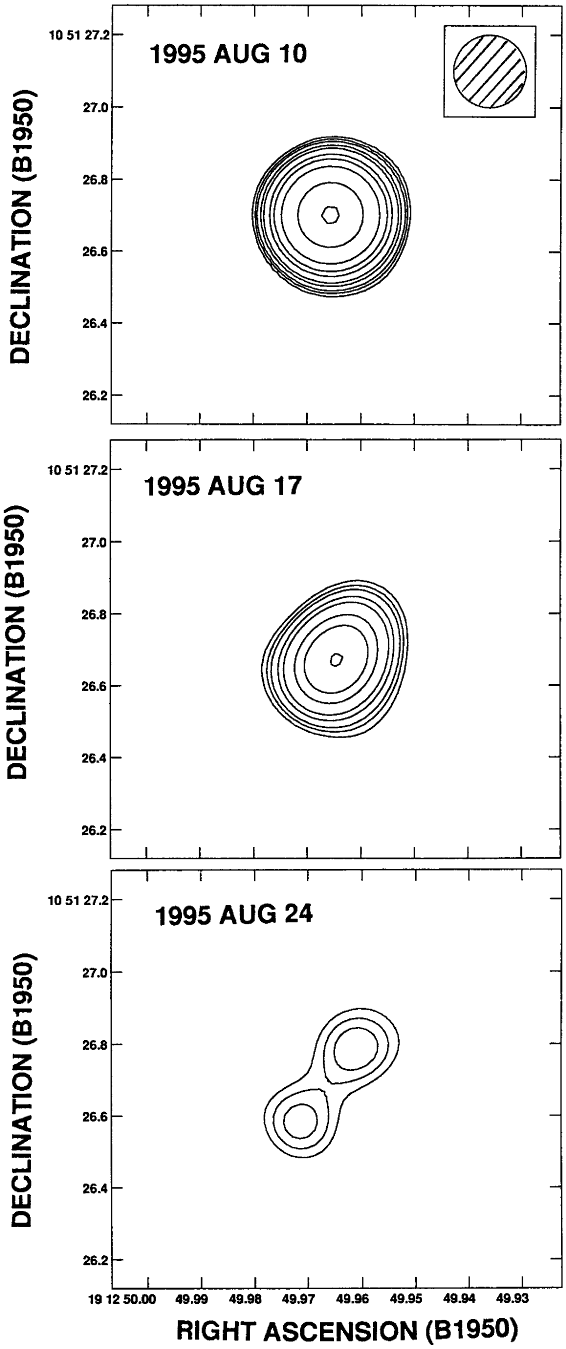

FIG. 2.—Pair of radio condensations emerging from GRS 1915+105 at the time of the 1995 August 10 flare shown in Fig. 1. These uniform-weight VLA-A maps were made at $\lambda = 3.5$ cm for the 1995 epochs shown on the top left of each map. The half-power beamwidth of 0.″2 is shown in the top right corner. Contours are 4, 5, 6, 10, 15, 20, 30, 60, and 100 times 4×10^{-3}, 8×10^{-5}, and 1.8×10^{-5} Jy beam^{-1} for the 1995 August 10, August 17, and August 24 epochs, respectively.

Other alternatives for the origin of the enhancement in the near-infrared flux could be synchrotron emission from relativistic jets (Sams, Eckart, & Sunyaev 1996), Doppler-broadened spectral line emission from entrained ions in the relativistic ejecta (Mirabel et al. 1996), free-free emission from an X-ray–driven wind (van Paradijs et al. 1994), and free-free emission from an expanding high-density envelope (Allen 1984). The observed reddening of the source by $J - K = 1.2$ mag rules out the possibility that we have seen the infrared tail of free-free emission, since the latter would have produced the opposite spectral change, namely, a blueing of the source, rather than the observed reddening.

The 1.0–2.5 μm continuum rising to the red is characteristic of thermal emission from dust. Furthermore, depending on the properties of the grains, dust is known to sublimate at ~2000–3000 K, and since it hardly radiates in the *J* band, the cutoff of the enhanced radiation below ~1.45 μm (see Table 2) is a stringent limit in favor of reradiation by heated dust (Voit 1991).

We point out that a trend toward redder colors as the star becomes brighter had also been observed in SS 433 (Catchpole et al. 1981), the other high-mass X-ray binary source of relativistic jets. However, those observations were carried out before coming to the realization of the role of interstellar dust in the dissipation of energy.

4.2. *Heated Dust in the Surroundings of GRS 1915+105*

In the following, we assume that the variation of the near-infrared flux is due to the appearance of a dust component in the spectrum of the source. In that case, the flux emitted by this dust component in *K* is related to the observed increase in magnitude by

$$f^K_{\rm dust} = f^K_0 \; 10^{-K^{\rm before}/2.5} \; (10^{-\Delta K/2.5} - 1) , \tag{1}$$

where $K^{\rm before}$ is the extinction-corrected apparent magnitude of the source before the rise consecutive to the outburst, ΔK is the magnitude increase, i.e., $K^{\rm after} - K^{\rm before}$, and f^K_0 is the *K* flux corresponding to $K = 0$, ~650 Jy (Allen & Cragg 1983). With $\Delta K = -1.1$ mag from Table 2, and $K^{\rm before} = 10.9$ mag using an interstellar extinction $A(K) = 2.4$ mag (Chaty et al. 1996), for a distance of 12.5 kpc (Rodríguez et al. 1995) we obtain an enhancement of ~60 $L_\odot$ in the *K* band. Similarly, it is found that the enhanced luminosity in the *H* band was ~130 $L_\odot$.

The temperature of the emitting dust can be derived assuming that its emission follows a blackbody spectrum modified by the emissivity of the dust component. Taking the ratio of the flux emitted at *H* and *K*, a dust temperature $T_d = 2300$ K is obtained. Integrating over the whole infrared band, the total dust luminosity at $T_d = 2300$ K is close to 10^3 $L_\odot$, namely, about 10% of the mean X-ray luminosity of the source at outburst (Harmon et al. 1996).

Figure 1*b* suggests that the source radiated about half that luminosity for a period of ~20 days, which implies that the emission from warm dust for the duration of the outburst was ~3×10^{42} ergs, which is ~10^{-3} the typical kinetic energy of the relativistic ejecta in GRS 1915+105 (Rodríguez & Mirabel 1996).

Finally, assuming that the source itself is optically thin in the near-infrared wavelengths, one can relate the emitted flux to the temperature and the total dust mass by

$$M_{\rm dust} = \frac{f_\nu D^2}{\kappa_\nu B_\nu(T_{\rm dust})} , \tag{2}$$

where κ_ν is the absorption coefficient of the dust per unit mass and *D* is the distance to the source. Combining equations (1) and (2), one obtains

$$M_{\rm dust} = 4.15\; 10^{-10}\; 10^{-K^{\rm before}/2.5}$$
$$\times\, (10^{-\Delta \rm K/2.5} - 1)(\rm e^{6524/T_d} - 1)\; D^2_{\rm kpc} , \tag{3}$$

in solar masses, which gives 1.2×10^{-10} $M_\odot$ of dust at $T_d \sim 2300$ K. We point out that the mass of cold dust components could be orders of magnitude larger, and it is possible that in the near-infrared we have just seen the tip of an iceberg in the surroundings of GRS 1915+105. Indeed, at a distance of 500 AU (3 light-days) and with an X-ray luminosity of 10^{37} ergs $\rm s^{-1}$ we expect an equilibrium dust temperature of only ~100 K (Scoville & Kwan 1976). We believe then that the near-IR emission observed could be coming from small grains out of equilibrium with the X-ray field, and that most of the dust is radiating at lower temperatures. Sensitive IR observations at longer wavelengths with the Infrared Space Observatory (ISO) will be carried out to test this hypothesis.

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. We thank C. Lidman and M. Hawkins for taking infrared images on the 2.2 m ESO telescope. UKIRT is operated by the Carnegie Observatories, on behalf of the UK Particle Physics and Astronomy Council. We are grateful to B. A. Harmon for providing us information on the BATSE data, and S. Sazonov for the *GRANAT*/WATCH data. We also thank M. Morris, L. Sage, and an anonymous referee for useful comments. L. F. R. acknowledges support from DGAPA, UNAM, and CONACyT, Mexico.

REFERENCES

Allen, D. A. 1984, MNRAS, 207, 45p
Allen, D. A., & Cragg, T. A. 1983, MNRAS, 203, 777
Catchpole, R. M., Glass, I. S., Carter, B. S., & Roberts, G. 1981, Nature, 291, 392
Chaty, S., Mirabel, I. F., Duc, P. A., Wink, J. E., & Rodriguez, L. F. 1996, A&A, 310, 825
Eikenberry, S. S., & Fazio, G. G. 1995, IAU Circ., No. 6267
Foster, R. S., Waltman, E. B., Tavani, M., Harmon, B. A., Zhang, S. N., Paciesas, W. S., & Gihgo, F. D. 1996, ApJ, 467, L81
Gihgo, F. D., Waltman, E. B., & Foster, R. S. 1995, IAU Circ., No. 6204
Harmon, B. A., Deal, K. J., Paciesas, W. S., Zhang, S. N., Gerard, E., Rodríguez, L. F., & Mirabel, I. F. 1996, ApJ, submitted
Harmon, B. A., Paciesas, W. S., & Fishman, G. J. 1995, IAU Circ., No. 6204
Mirabel, I. F., Bandyopadhyay, R., Charles, P. A., Shahbaz, T., & Rodríguez, L. F. 1996, ApJ, submitted
Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46
Mirabel, I. F., et al. 1994, A&A, 282, L17
Rodríguez, L. F., Gerard, E., Mirabel, I. F., Gómez, Y., & Velázquez, A. 1995, ApJS, 101, 173
Rodríguez, L. F., & Mirabel, I. F. 1996, ApJ, submitted
Sams, B. J., Eckart, A., & Sunyaev, R. 1996, Nature, 382, 47
Sazonov, S. Yu., Sunyaev, R. A., & Lund, N. 1996, in Proc. Röntgenstrahlung from the Universe, ed. H. U. Zimmermann, J. E. Trümper, & H. Yorke (Garching: MPE), 187
Scoville, N. Z., & Kwan, J. 1976, ApJ, 206, 718
van Paradijs, J., Telesco, C. M., Kouveliotou, C., & Fishman, G. J. 1994, ApJ, 429, L19
Voit, G. M. 1991, ApJ, 379, 122