COMPTEL observations of GRO J1655-40

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ABSTRACT

GRO J1655-40 is a transient black-hole candidate that has been shown to eject matter at apparently superluminal velocities. OSSE spectra measured during X-ray outbursts are consistent with a single power law up to $\sim$ 600 keV, with no evidence for a high-energy cutoff. Flaring behaviour of GRO J1655-40 has also been claimed to be detected up to 10 MeV during observations with the balloon-borne HIREGS instrument in January 1995.
Here we present the analysis of COMPTEL observations (0.75–30 MeV) of this source. Before April 1996, GRO J1655-40 was in the field-of-view of COMPTEL during $\sim$ 50 CGRO viewing periods. We present upper limits on the time-averaged emission from GRO J1655-40 and also search for γ-ray flares in 200 intervals of two days each.

Keywords: Gamma rays: observations – Binaries: general – Stars: individual: GRO J1655-40– Black holes

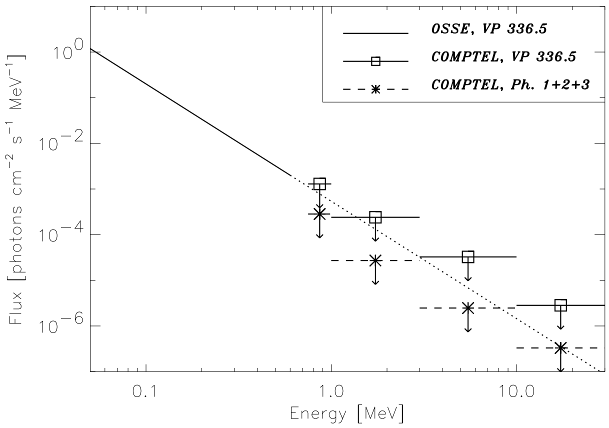

Figure 1: The COMPTEL 2σ upper limits obtained for GRO J1655-40 during VP 336.5 (squares) and during the first 40 months of the CGRO mission (asterisks). Also shown are the OSSE spectrum measured for GRO J1655-40 during VP 336.5 (solid line) and its extrapolation (dotted line).

1. INTRODUCTION

GRO J1655-40 is a transient X-ray binary which was discovered with BATSE on July 27, 1994 (Zhang et al. 1994). The mass-function determined for this system (the lower limit to the mass of the compact object) is 3.16 ± 0.15 $M_\odot$ (Bailyn et al. 1995), which places GRO J1655-40 in the subgroup of black-hole candidates. Like GRS 1915+105, GRO J1655-40 ejects matter at apparently superluminal motion. Such ejections are accompanied by a strong increase of the X-ray flux (Harmon et al. 1995). OSSE observations during several of these outbursts show a power-law spectrum up to $\sim$ 600 keV with no sign of a high-energy cut-off (Kroeger et al. 1996; see also Fig. 1).
In the sum of all observations from the first 40 months of the CGRO mission, no significant time-averaged MeV emission was detected with COMPTEL from this source (van Dijk 1996). Also for the dedicated COMPTEL observations performed during the large outburst in August 1994 only upper limits were obtained (McConnell 1995). These upper limits lie above the extrapolation of the 50-600 keV power-law spectrum observed contemporaneously with OSSE (Fig. 1).
During observations in January 1995, the balloon-borne HIREGS instrument detected a strong transient γ-ray flare from GRO J1655-40 (Boggs et al. 1996). The emission between 1 MeV and 10 MeV could be described by a power-law spectrum and was only observed on one day, January 12, which put an upper limit on the duration of the flare of $\sim$ 1 day. Here we report on a search for this flare in the COMPTEL data, and on a search for other γ-ray flares from GRO J1655-40 using all relevant COMPTEL observations from the first 5 years of the CGRO mission.

2. THE INSTRUMENT

COMPTEL is an imaging Compton-scattering telescope, sensitive to γ-rays with energies between $\sim$ 0.75 and 30 MeV (for a complete description of the instrument, see Schönfelder et al. 1993). Events are defined by two coïncident interactions in the two detectors (separated by 1.58m) and can be caused both by celestial photons scattering from the upper to the lower detector, and by the instrumental-background radiation. Among the measured variables for each event are the energy deposits and interaction locations in the two detectors. The measured scattering angle $\bar{\varphi}$ is calculated from the energy deposits using the Compton formula and is equal to the true scattering angle φ_g only if no energy losses occurred.
Due to the characteristics of the Compton-scattering process, COMPTEL has a large field-of-view which extends up to several tens of degrees. The effective exposure accross the sky for standard event selections typically resembles a two-dimensional Gaussian, with an energy-dependent FWHM which is $\sim 57°$ in the 1–3 MeV range (i.e., at 30° from the pointing direction the effective exposure has dropped by a factor of ~ 2). By relaxing certain event selections, such as on the energy deposits and on the measured scattering angle $\bar{\varphi}$, it is possible to extend the effective exposure to larger angles.
For the analyis of COMPTEL data, a model for the distribution of the instrumental background in data space is required. Here we used two closely related models (known as `BGDLCF` and `SRCLIX`) which involve a smoothing of the data themselves (see Bloemen et al. 1994, van Dijk 1996).

3. ANALYSIS AND OBSERVATIONS

The outburst of GRO J1655-40 observed with HIREGS occurred during CGRO Viewing Period (VP) 409, which started on January 10, 1995, and lasted until January 24, 1995. During this observation, GRO J1655-40 was at an angular distance ($\equiv Z$) of $\sim 75°$ from the pointing direction of COMPTEL. We first investigated the response of COMPTEL at large Z using observations of the Crab (see Table 1). Subsequently we determined the COMPTEL upper limits for GRO J1655-40 during the complete VP 409 and also during a two-day interval containing the HIREGS outburst (January 12-13, 1995). The length of the latter interval was chosen to be twice the upper limit of $\sim$ 1 day on the duration of the MeV flare as gathered from Boggs et al. 1996. It is also regarded a safe minimum required for the instrumental-background modelling used.
For the search for the possible occurrences of γ-ray flares during other epochs, we used all available data from the first 5 years of the CGRO mission during which GRO J1655-40 was within 50° of the pointing direction. These data were divided into 200 intervals of $\sim$ 2 days each.
Note that the upper limit on the duration of the January 12 flare (1–10 MeV) is now of the order of 1 hour (S. Boggs, private communication; see also last paragraph before Section 5).

The analyses presented here are performed in the 3-dimensional COMPTEL data space (see Schönfelder et al. 1993) and are based on the Maximum-Likelihood-Ratio (MLR) method. A description of the application of this method to COMPTEL data can be found in de Boer et al. 1992. The quantities that are obtained for each sky pixel are the MLR value itself, which is a measure for the detection significance of a source at that location, and a flux and corresponding 1σ error. It is also possible to incorporate certain known or assumed celestial distributions, such as the Galactic diffuse emission, in the analysis. This is achieved by folding the celestial distribution through the response function and fitting the resulting 3-dimensional distribution in data space, together with the instrumental-background model, to the observed event distribution.

VP	l [°]	b [°]	Z [°]	T [days]
26.0+28.0	108.8	−41.4	75.5	21
30.0+33.0	252.4	30.6	74.3	21
418.0	158.0	65.9	74.2	14
503.0	104.0	−2.0	80.4	7
504.0	111.0	−10.0	72.9	7
505.0	118.0	−2.0	66.5	7
506.0	111.0	5.0	74.2	7

Table 1: The observations of the Crab used in the analysis of the large-angle response. Column 1*: the CGRO VP no.;* column 2 and 3*: the Galactic longitude and latitude of the pointing direction;* column 4*: the angular distance Z between the pointing direction and the location of the Crab;* column 5*: the duration of the VP.*

4. RESULTS

4.1. The Crab at a large angular distance from the pointing direction

Using standard event selections, only the MLR map for the 1.25–3.0 MeV range in VP 506 exhibits a point-source-like feature that is positionally consistent with the Crab. The maps for all other energy ranges and VPs lack such a feature. This is probably due to the fact that for these large-angle observations the number of events from the Crab in the data space N is small in a 1-week observation, typically only 50 in the 1.25–3.0 MeV energy range.
Two ways to increase N are to relax the lower boundary of the selection on E_2 (the energy deposit in the lower detector), and to decrease ζ (the minimum angle between the projected event circle and the Earth's horizon). Depending on the VP, these wider event selections typically increase N by factors of ~ 3 and ~ 2 respectively. Despite this, in neither of the cases a significant detection was found. This may be due to the inaccurate response description used, which neglects the spread in hardware energy thresholds in the lower detector, and to the increase in the number of events due to photons coming from the Earth's horizon. Also, the background models used were designed for and tested on data spaces up to $\bar{\varphi} \sim 50°$ and may not be optimal for the larger $\bar{\varphi}$ values actually used in this study.
From the above, we can state that a source of a strength similar to the Crab is not detectable in a

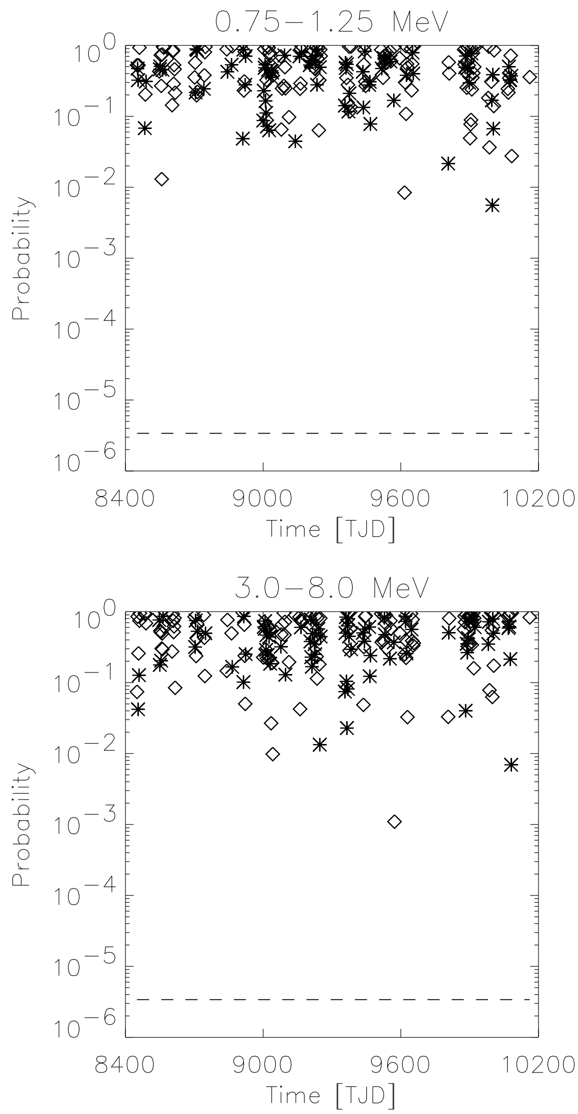

Figure 2: The probabilities that the deviations of fluxes measured in two-day intervals from the zero-level fluxes are just statistical fluctuations (see also text Section 4.3). The dashed lines indicate the 3σ confidence level for a significant detection of time variability. The diamonds and asterisks refer to positive and negative flux values respectively.

typical 1-week observation when Z(source) is $\sim 75°$. Note that the upper limits obtained in each of these cases are consistent with (i.e. higher than) the Crab fluxes.

4.2. GRO J1655-40 in January 1995

The HIREGS observations of the γ-ray flare from GRO J1655-40 in January 1995 indicated fluxes that are larger than that of the Crab by a factor of ~ 5 at 1 MeV and by a factor ~ 50 at 10 MeV (Boggs et al. 1996). An analysis of the COMPTEL data for VP 409 (Z(GRO J1655-40) $\sim 75°$), both using all data and limiting it to two days containing the outburst, did not yield a detection of significant emission from the position of GRO J1655-40. Upper limits on the γ-ray flux in the different energy ranges can be found in Table 2. These upper limits are quite high due to the large angular distance of GRO J1655-40 to the pointing direction and do not constrain the HIREGS measurement of the flare, especially if one takes into account their current upper limit on the duration of the flare of ~ 1 hour.

4.3. A search for γ-ray flares from GRO J1655-40 in ~ 5 years of COMPTEL data

For each of the 200 time intervals in 4 energy ranges (0.75–1.25, 1.25-3.0, 3.0–8.0 and 8.0–30.0 MeV), we determined the MLR value, the flux and 1σ error at the location of GRO J1655-40. Since we are interested in time variations only, as opposed to absolute fluxes, data-space models for the Galactic diffuse emission were not included in this step. Most of the MLR values thus found were not significant, i.e., the fluxes were consistent with 0. Chi-square fits to the time series in the 4 energy ranges were used to determine the levels of these zero-level fluxes. The reduced χ^2 values of these fits are 1.25, 1.18, 1.03 and 0.93 respectively, none of which indicates significant time

E [MeV]	UL_F	UL_C
January 12-13		
1.25–3.0	$< 8.2 \times 10^{-3}$	< 20
3.0–8.0	$< 1.1 \times 10^{-3}$	< 15
8.0–30.0	$< 6.2 \times 10^{-4}$	< 91
VP 409 complete		
1.25–3.0	$< 2.5 \times 10^{-3}$	< 6
3.0–8.0	$< 9.5 \times 10^{-4}$	< 13
8.0–30.0	$< 2.8 \times 10^{-4}$	< 41

Table 2: The 2σ upper limits obtained for GRO J1655-40 in VP 409 (January 10-24) and during a subset of these data. Column 1*: the energy range;* column 2*: the flux upper limit in photons cm^{-2} s^{-1} MeV^{-1};* column 3*: the flux upper limit in terms of the Crab flux.*

variability at more than the 3σ level *when prior knowledge about possible time variability does not exist.*

To investigate any possible time variability of the few positive measurements correlated with, e.g., the hard X-ray flux, we applied the F-test for each time interval with a second model, consisting of a flux constant in time and a delta function. In Fig. 2 we show the probabilities calculated from these F-tests, each of which indicates the probability that the deviation in that time interval from the constant zero-level flux is just a statistical fluctuation. The dashed lines at probability levels of 3.4×10^{-6} indicate the 3σ confidence levels, calculated assuming a number of 800 trials (4 energy ranges and 200 time intervals). Again, there is no evidence for significant time variability at more than the 3σ level. The fluxes required in a single time interval to obtain a probability of 3.4×10^{-6} would be 1.7, 1.5, 1.7 and 3.0 Crab units in the four energy ranges.

Out of the 800 MLR maps, only 5 exhibit point-source-like features which are consistent with the location of GRO J1655-40 and which have an MLR value that is greater than 9 (Table 3). Remarkably, 3 of these 5 time intervals fall in the period August-September 1994, when GRO J1655-40 was seen to be flaring at other wavelengths as well (Harmon et al. 1995). A comparison of the hard X-ray lightcurve (Harmon et al. 1995) with the γ-ray data, however, does not reveal a clear one-to-one correlation. Since the most significant measurements (Table 3) also occur in different energy ranges, we do not regard them as positive detections of GRO J1655-40.

A more recent analysis of the HIREGS data obtained during January 12, 1995, indicated that the 1-10 MeV emission lasted less than 1 hour (S. Boggs, private communication). Such short outbursts, even if the flux levels reach several Crab units, will have been missed in the search presented here. We are presently developing the tools to search the COMPTEL data on GRO J1655-40 and other black-hole candidates for γ-ray flares on timescales of ~ 1.5 hours (1 orbit of the CGRO satellite). In this respect, we note that BATSE has observed short-lived very strong 20-100 keV flares from GRS 1915+105, a black-hole candidate similar to GRO J1655-40, on timescales of ~ 15 minutes (Paciesas et al. 1996).

E [MeV]	T	T [TJD]	MLR
0.75–1.25	Sep. 20–22, 1994	9615–9617	9.8
1.25–3.0	Sep. 2–3, 1993	9232–9233	13.7
3.0–8.0	Feb. 22–25, 1993	9040–9043	9.1
	Aug. 7–9, 1994	9571–9573	14.4
8.0–30.0	Aug. 29–31, 1994	9593–9595	13.7

Table 3: The time intervals for which the MLR value at the location of GRO J1655-40 was greater than 9 (a value of 9 indicates a 3σ detection for a source at a known location). Column 1*: the energy range;* column 2*: the start and end date of the interval;* column 3*: the same as column 2, but now in TJDs;* column 4*: the MLR value at the location of GRO J1655-40.*

5. CONCLUSIONS

Due to the unfavorable pointing direction of CGRO in VP 409, the COMPTEL data cannot confirm, nor refute, the HIREGS detection of a huge γ-ray flare from GRO J1655-40 between 1 MeV and 10 MeV on January 12, 1995. A search for such γ-ray flares in ~ 5 years of COMPTEL data did not reveal evidence for the occurence of strong flares on timescales of ~ 2 days. A search for γ-ray flares on much shorter timescales of ~ 1 hour, from GRO J1655-40 and from other black-hole candidates such as GRS 1915+105 and Cyg X-1, is underway.

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