2002

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Recommended Citation

Wijnands, R and Wang, QD, "A Chandra Observation of GRO J1744–28: The Bursting Pulsar in Quiescence" (2002). *The Astrophysical Journal Letters*. 1060.

https://doi.org/10.1086/340332

Re-submitted to ApJ Letters: February 12, 2002

A *Chandra* observation of GRO J1744–28: the bursting pulsar in quiescence

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ABSTRACT

We present a *Chandra*/ACIS-I observation of GRO J1744–28. We detected a source at a position of R.A = $17^h\ 44^m\ 33.09^s$ and Dec. = $-28^\circ\ 44'\ 27.0''$ (J2000.0; with a 1σ error of ~0.8 arcseconds), consistent with both *ROSAT* and interplanetary network localizations of GRO J1744–28 when it was in outburst. This makes it likely that we have detected the quiescent X-ray counterpart of GRO J1744–28. Our *Chandra* position demonstrates that the previously proposed infrared counterpart is not related to GRO J1744–28. The 0.5–10 keV luminosity of the source is $2-4\times10^{33}$ erg s^{-1} (assuming the source is near the Galactic center at a distance of 8 kpc). We discuss our results in the context of the quiescent X-ray emission of pulsating and non-pulsating neutron star X-ray transients.

Subject headings: pulsars: individual (GRO J1744–28) — stars: neutron — X-rays: stars

1. Introduction

X-ray transients sporadically exhibit very bright outbursts during which their X-ray luminosity can be as high as 10^{36-39} erg s^{-1}. However, most of their time they are in their quiescent state during which they emit X-rays only at a level of 10^{30-34} erg s^{-1}. The mechanisms behind this quiescent X-ray emission are still not understood (see, e.g., Menou et al. 1999; Campana & Stella 2000; Bildsten & Rutledge 2002). The most dominant model

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for the quiescent properties of non-pulsating neutron star transients, which contain a neutron star with a very low magnetic field ($< 10^{10}$ Gauss), is the one which assumes that the X-rays below a few keV are due to the cooling of the neutron star after the accretion has stopped (see, e.g., Brown, Bildsten, & Rutledge 1998 and references therein). In the quiescent X-ray spectra of several of those systems an extra power law component above a few keV is present (see, e.g., Asai et al. 1996, 1998; Campana et al. 1998a; Rutledge et al. 2001), but the nature of this component is even more unclear (see, e.g., Campana & Stella 2000 for a discussion).

Detailed studies of the quiescent emission from transient X-ray pulsars (with a neutron star magnetic field strength of $> 10^{11}$ Gauss) have been inhibited by the lack of detected systems. So far, only two X-ray pulsars have been detected in quiescence, A 0535+26 (Negueruela et al. 2000) and 4U 0155+63 (Campana et al. 2001). Their X-ray luminosities were consistent with the predictions of the cooling neutron star model for the non-pulsating systems, suggesting that also this model might apply to the pulsating ones. However, due to the low statistics of the data a detailed testing of the model could not be performed. To get more insight in the quiescent emission of X-ray pulsars those systems have to be observed with higher sensitivity instruments like *Chandra* or *XMM-Newton*. Furthermore, more quiescent X-ray pulsars have to be detected to determine if all of those systems are consistent with the cooling model or that some systems might have different properties which would suggest alternative X-ray production mechanisms (e.g., accretion down to the magnetospheric radius; Stella et al. 1994; Corbet 1996). A good candidate for such studies is the "bursting pulsar" GRO J1744–28.

GRO J1744–28 was discovered in December 1995 with the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma-Ray Observatory* (*CGRO*; Fishman et al. 1995; Kouveliotou et al. 1996). The source exhibited rapidly repeating, very bright X-ray bursts which are likely due to accretion disk instabilities (e.g., Lewin et al. 1996). The source also exhibited pulsed emission with a pulsation frequency of 2.1 Hz (Finger et al. 1996). Its bursting and pulsating nature lead to the source being called the bursting pulsar. So far, two major outbursts have been detected, one starting in December 1995 and the other one a year later in December 1996. The latter one ended in April 1997 (see, e.g., Woods et al. 1999).

Augusteijn et al. (1997) likely detected GRO J1744–28 using a *ROSAT* observation performed in March 1996. This observation showed a bright source with a luminosity of $\sim 2 \times 10^{37}$ erg s^{-1} (for an assumed distance[4] of 8 kpc; 0.1–2.4 keV). Archival *ROSAT*

[4]The distance to the source is unknown but the high column density measured by Nishiuchi et al. (1999)

observations did not detect a source on this position with an upper limit on the luminosity of a few times 10^{33} erg s^{-1} (0.1–2.4 keV; Augusteijn et al. 1997). This transient nature of the source makes it very likely that indeed the *ROSAT* source is GRO J1744–28 despite that no bursts or pulsations were detected (note that the large *ROSAT* upper limit on the pulsations obtained by Augusteijn et al. 1997 was completely consistent with the strength of the pulsations as measured with BATSE and the *Rossi X-ray Timing Explorer* [*RXTE*]). Localization of GRO J1744–28 by triangulating the data obtained for this source with *Ulysses* and BATSE (part of the interplanetary network [IPN]) resulted in a position (Hurley et al. 2000) which partly overlapped that of the *ROSAT* error circle, confirming the identification of the *ROSAT* source with GRO J1744–28. Cole et al. (1997) and Augusteijn et al. (1997) identified a possible infrared counterpart at the edge of the *ROSAT* error circle, although its enigmatic properties spurred the suggestion that it might be an instrumental artifact (Augusteijn et al. 1997; but see Cole et al. 1997).

Here we present a *Chandra*/ACIS-I observation of the region containing GRO J1744–28. We discovered a weak source near the center of the *ROSAT* error circle, which is likely the quiescent counterpart of the *ROSAT* transient and therefore likely of GRO J1744–28.

2. Observation, analysis, and results

GRO J1744–28 was in the field of view (∼7.1 arcminutes off-axis) during one of the observations which were obtained as part of the *Chandra* survey of the Galactic Center region (Wang, Gotthelf, & Lang 2002). This particular observation was performed on 2001 July 18 17:37 - 20:49 UT with an exposure time of ∼ 10.6 ksec. The ACIS-I instrument was used during this observation. To limit the telemetry rate only those photons with energy above 1 keV were transmitted to Earth. The data were analysed using the analysing packet CIAO, version 2.2.1, and the threats listed on the CIAO web pages[5].

The resulting image of the region near GRO J1744–28 is shown in Figure 1. We detected one source in the *ROSAT* error circle (Augusteijn et al. 1997) and the IPN error ellipse (Hurley et al. 2000) of GRO J1744–28. This strongly suggests that indeed we have detected the quiescent counterpart of GRO J1744–28. The best source position (as obtained with the CIAO tool WAVDETECT) is R.A. = $17^h\ 44^m\ 33.09^s$ and Dec. = $-28^\circ\ 44'\ 27.0''$ (for J2000.0). Due to the low number of detected photons the statistical error on the source position

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and the proximity of the source on the sky to the center of the Galaxy make a large distance likely.

[5]Available at http://asc.harvard.edu/ciao/

is 0.3 arcseconds. However, the satellite pointing error is approximately 0.7 arcseconds (1σ; Aldcroft et al. 2000) and dominates the positional inaccuracy. The proposed infrared counterpart (Cole et al. 1997; Augusteijn et al. 1997) is not consistent with our *Chandra* position.

The elongated structure of the detected source in Figure 1 is due to the extended point-spread-function for a point source approximately 7 arcminutes off-axis. We detected 52 ± 8 counts (corrected for background) from the source position, resulting in a count rate of $4.9 \pm 0.7 \times 10^{-3}$ counts s^{-1}. The source spectrum was extracted using a circle with a radius of $10''$ on the source position[6]. The background data were obtained by using an annulus on the same position with an inner radius of $10''$ and an outer one of $30''$. The data were rebinned using the FTOOLS routine grppha into bins with a minimum of 5 counts per bin. We employed both the χ^2 and CASH (Cash 1979) statistics to fit the data. Both methods give very similar results and we will only discuss the results obtained with the χ^2 method. The obtained spectrum was fitted using XSPEC version 11.1.0 (Arnaud 1996).

The spectrum (Fig. 2) was of poor quality and every single-component model provided an acceptable fit ($\chi^2/dof \lesssim 1$). The column density could not be constrained and was fixed to the value as determined using *ASCA* data ($N_{\rm H} \sim 5.5 \times 10^{22}$ cm^{-2}; Nishiuchi et al. 1999) during times when the source was in outburst. A pure power-law model resulted in a photon index of 2.4 ± 0.7 (all fit parameters are for a 95% confidence level) and a flux of 5.3×10^{-13} erg cm^{-2} s^{-1} (0.5–10 keV; unabsorbed; all subsequent fluxes are for this energy range and unabsorbed). A blackbody model resulted in a temperature kT of 0.8 ± 0.2 keV, with a radius of the emitting region of only $0.2^{+1.6}_{-0.9}$ km (assuming a distance of 8 kpc), and a flux of 2.5×10^{-13} erg cm^{-2} s^{-1}. When fitting a neutron star hydrogen atmosphere model (Zavlin, Pavlov, & Shibanov 1996) to the data, the radius of the emitting region could not be constrained and was fixed to 10 km. The obtained temperature at infinity kT_∞ was 0.4 ± 0.2 keV and the resulting flux is 3.0×10^{-13} erg cm^{-2} s^{-1}. The uncertainties in which spectral model to use resulted in a possible range for the flux of $2.5 - 5.3 \times 10^{-13}$ erg cm^{-2} s^{-1}. If the source is indeed near the Galactic center at a distance of ~ 8 kpc, then the 0.5–10 keV luminosity would be in the range of $2 - 4 \times 10^{33}$ erg s^{-1}.

When the quiescent spectrum of non-pulsating neutron star X-ray transients are fit with a single component model consisting of either a blackbody or a neutron star atmosphere model, the obtained temperatures are usually 0.2–0.3 keV (using a blackbody model; e.g., Bildsten & Rutledge 2002 and references therein) or ~ 0.1 keV (using a neutron star

[6]For a $\sim 7'$ off axis source an extraction radius of $10''$ ensures that virtually all source photons are extracted and that no contamination of source photons occurs in the background region.

atmosphere model). Our spectrum of GRO J1744–28 is not consistent with such low temperatures ($\chi^2/dof > 3$): both the blackbody and the neutron star atmosphere model fall-off more rapidly at energies above 1 keV than our data. However, several of those non-pulsating systems have displayed a composite quiescent X-ray spectrum, with a soft, most likely thermal component below ~ 1 keV and a hard, power-law type component at higher energies (e.g., Asai et al. 1996, 1998). We have fitted our data using such a composite spectrum consisting of either a blackbody or a neutron star atmosphere model for the soft component and a power-law with photon index of 1 or 2 for the hard component. However, due to the low number of photons detected and the high column density towards the source, no constraints could be set on the temperature of the soft component. The data are fully consistent with the temperatures observed for other systems (e.g., a blackbody temperature of 0.2–0.3 keV) and with an upper limit on the thermal flux of 3×10^{-13} erg cm^{-2} s^{-1} (0.5–10 keV; for a kT of 0.3 keV) or 9×10^{-13} erg cm^{-2} s^{-1} (for a kT of 0.2 keV).

The detected source was the only one present in the *ROSAT* error circle and the IPN ellipse. Hands et al. (2002) reported on *XMM-Newton* observations performed on the Galactic plane to study the Galactic X-ray point source population. Using their log N – log S curve and a 2–6 keV flux of $\sim 1 - 2 \times 10^{-13}$ erg cm^{-2} s^{-1} for GRO J1744–28, we estimate that about 10 to 20 sources per square degree can be detected with the same flux. This gives a probability of $\sim 1 - 2 \times 10^{-4}$ that a random field source would fall in the surface area traced out by the intersection of the *ROSAT* error circle and the IPN error ellipse. The source density will likely be higher in the Galactic center region which would increase this probability. But the calculated probability can be used as a first approximation and it indicates that the detected source is likely GRO J1744–28. However, if the detected *Chandra* source is not GRO J1744–28, then the flux upper limit on this source would be about $2 - 5 \times 10^{-14}$ erg cm^{-2} s^{-1} (depending on which spectral model is assumed). Our observation had a time resolution of only ~ 3.2 seconds, which did not allow us to search for the 2.1 Hz pulsations. The low number of photons detected did not allow for a stringent conclusion on the possible variability of the source on longer time scales.

3. Discussion

We detected a *Chandra* source in the *ROSAT* error circle (Augusteijn et al. 1997) and IPN ellipse (Hurley et al. 2000) of GRO J1744–28, making it likely that we have detected the quiescent X-ray counterpart of GRO J1744–28. The proposed infrared counterpart (Cole et al. 1997; Augusteijn et al. 1997) is not consistent with our *Chandra* position and the nature of this source is unclear (it might be, as suggested by Augusteijn et al. 1997, an artifact, although Cole et al. 1997 could not confirm this). Our quiescent flux of $2.5 - 5.3 \times 10^{-13}$ erg cm^{-2} s^{-1} (0.5–10 keV; unabsorbed) is consistent with the non-detection of GRO J1744–28 during the archival *ROSAT* observation reported by Augusteijn et al. (1997; using their count rate upper limit for GRO J1744–28, an 0.5–10 keV unabsorbed flux upper limit range can be derived using PIMMS[7] of $7 - 10 \times 10^{-13}$ erg cm^{-2} s^{-1}, depending on the spectral model).

One possible mechanism producing the quiescent emission is residual accretion on to the surface of the neutron star. However, Cui (1997) argued (based on the sudden decrease of the pulsation amplitude at times when the 2–60 keV flux of GRO J1744–28, as measured with *RXTE*, was below $\sim 2 \times 10^{-9}$ erg cm^{-2} s^{-1}) that GRO J1744–28 is in the "propeller" regime at relatively low fluxes. In this regime, the magnetic field of the neutron star inhibits accretion on to the neutron star surface. Our *Chandra* flux for GRO J1744–28 is much lower than the critical flux limit given by Cui (1997) strongly suggesting that the source was in the propeller regime during our observation. Therefore, accretion on to the surface of the neutron star is not likely to be the cause behind the quiescent X-ray emission of GRO J1744–28. Similar conclusions were also reached for the quiescent emission from the transient X-ray pulsars A 0535+26 (Negueruela et al. 2000) and 4U 0155+63 (Campana et al. 2001).

A possible mechanism to produce the observed quiescent X-rays when the source is in the propeller regime might be accretion down to the magnetospheric radius $r_{\rm m}$ (e.g., Stella et al. 1994; Corbet 1996; Campana et al. 1998b), which is approximately give by $(GM_{\rm ns})^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$, in which $M_{\rm ns}$ is the neutron star mass, μ the neutron star magnetic moment, and $\dot{M}$ the accretion rate. The luminosity produced will be $L = GM_{\rm ns}\dot{M}/r_{\rm m}$. Using our measured luminosity and the magnetic field strength found by Cui (1997; $\sim 2 \times 10^{11}$ Gauss), then $\dot{M} \sim 3 - 5 \times 10^{15}$ g s^{-1} and $r_{\rm m} \sim 2 - 3 \times 10^{8}$ cm. This radius is larger than the corotation radius $r_{\rm c} = (GM_{\rm ns})^{1/3}(P_{\rm spin}/2\pi)^{2/3}$ (with $P_{\rm spin}$ the neutron star spin period), which is $\sim 10^{8}$ cm for GRO J1744–28, and therefore it fulfills the condition that the source should be in the propeller regime. Although a rough estimate[8], it indicates that accretion down to the magnetospheric radius might be able to produce the quiescent X-ray luminosity of GRO J1744–28. However, contributions to the X-ray luminosity might also come from several other mechanisms, like accretion onto the neutron star surface (possibly on localized areas such as the magnetic poles) due to the leakage of matter through the magnetospheric

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[7]Available at http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html

[8]Large uncertainties are present in the exact luminosity of the source (due to uncertainties in the spectral shape and in the distance to the source), its magnetic field strength, and in certain unknown constants (like the accretion efficiency), which have been assumed to be roughly 1. A full detailed discussion of those uncertainties is beyond the scope of this *Letter*.

barrier.

Another contribution to the quiescent X-ray emission will be the thermal X-ray emission from the neutron star surface which should give a rock bottom lower limit on the X-ray luminosity. Due to the low statistics of our data and the high column density towards GRO J1744–28, we are not able to accurately probe such a thermal component. However, if the temperature of the thermal component is similar to what has been observed for the quiescent spectra of the non-pulsating neutron star transients, then at least the detected emission in our *Chandra* observation is mostly due to an another component, which has its origin probably in one of the above discussed mechanisms.

Progress in our understanding of the quiescent X-ray emission can be made for GRO J1744–28 by obtaining longer *Chandra* or *XMM-Newton* observations of this source. Such observations will be able to constrain its luminosity and spectral shape much better than we are able to due with the present *Chandra* data and will determine if the quiescent spectrum of GRO J1744–28 is similar to that of the quiescent non-pulsating systems, or that a fundamental difference is present. Detecting the pulsations in observations with sufficient time resolution will also constrain the mechanisms for the quiescent X-rays in this system. Detecting the pulsations in quiescence would also unambiguously proof that the detected source is GRO J1744–28.

Note added in manuscript: After submission of our paper, we became aware of the paper by Daigne et al. (2002) who reported on a *XMM-Newton* observation of GRO J1744–28 in quiescence. Their reported position and X-ray flux for the source are consistent with ours.

RW was supported by NASA through Chandra Postdoctoral Fellowship grant number PF9-10010 awarded by CXC, which is operated by SAO for NASA under contract NAS8-39073. WQD is supported by the CXC grant SAO-GO1-2150A. We thank Jon Miller for comments on a previous version of this letter.

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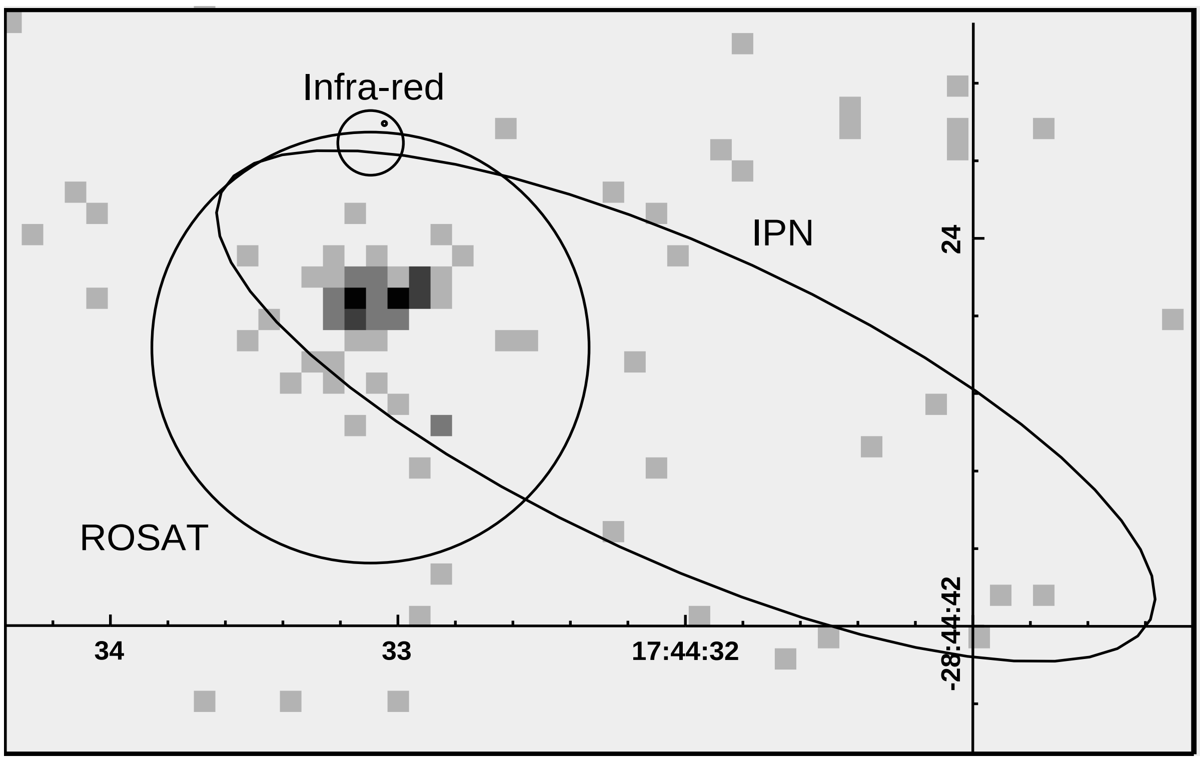

Fig. 1.— The *Chandra*/ACIS-I image (for photons with energy of 1 keV or higher) of GRO J1744–28, rebinned by a factor of 2. Due to the point-spread-function for off-axis point sources, the source appears to be extended, but it is consistent with being a point source. The coordinates are for epoch J2000.0. Also shown are the *ROSAT* error circle (Augusteijn et al. 1997), the IPN localization ellipse (Hurley et al. 2000) and the error circles of the possible infrared counterpart (Augusteijn et al. 1997: large; Cole et al. 1997: small). It is obvious that the *Chandra* source is consistent with the *ROSAT* and the IPN source, but not with the infrared source.

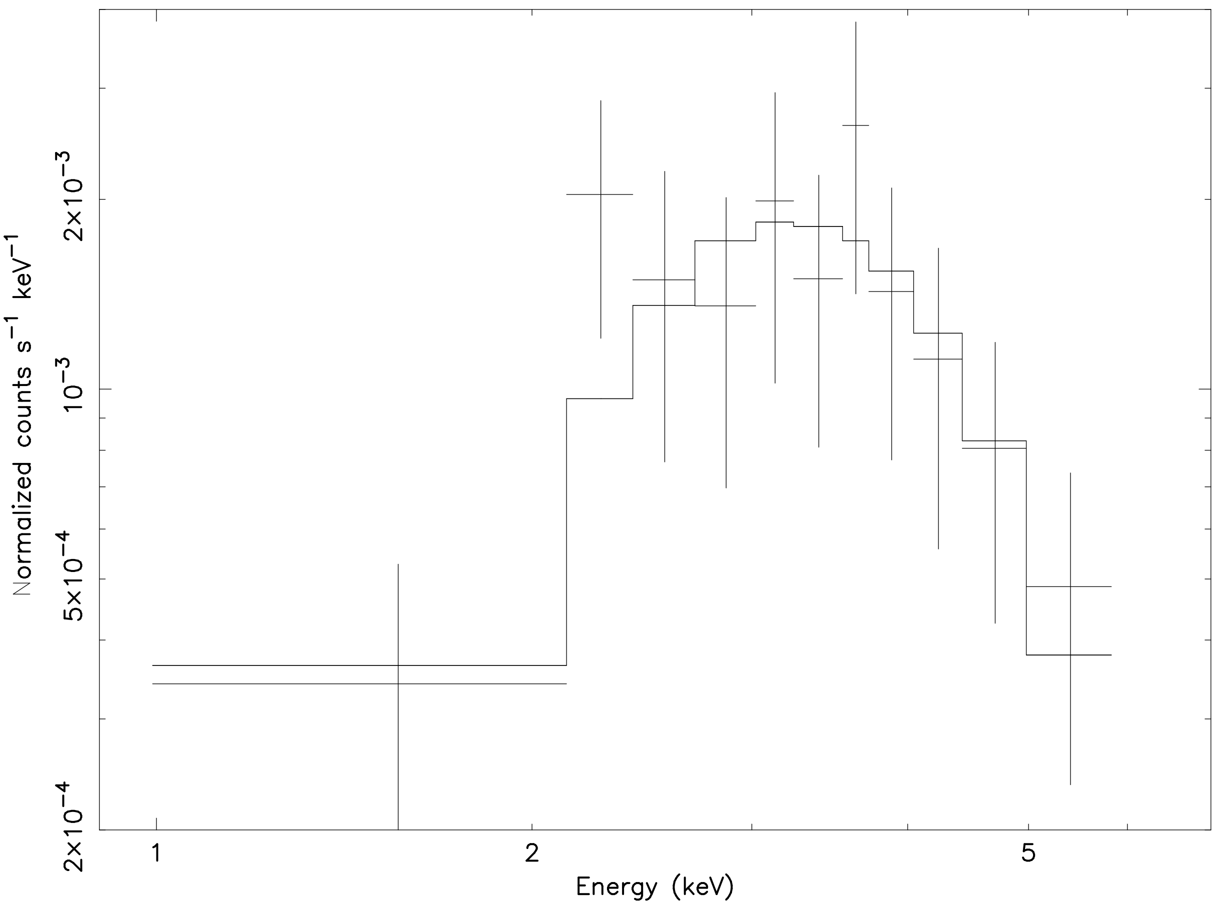

Fig. 2.— The energy spectrum (for photons above 1 keV) of GRO J1744–28 as measured with the *Chandra*/ACIS-I instrument. The solid line through the data is the best blackbody fit.