

BeppoSAX broad-band observations of Gamma Cassiopeiae

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Abstract. We report broad-band X-ray measurements of the Be star γ Cassiopeiae by the BeppoSAX X-ray astronomy satellite. The observations took place on 1998 July, 18–23. The 0.1–200 keV X-ray spectrum is reasonably well fit by an optically thin thermal plasma model of temperature 12.5 ± 0.6 keV with significant residuals around 0.3 keV and 1 keV. The former is interpreted as the variable soft component reported by ROSAT, although there is no evidence for variability at the 5% level. For a blackbody interpretation, the fitted temperature is $100 \pm_{13}^{320}$ eV, in agreement with the ROSAT value of 200 ± 10 eV. However, a MEKAL interpretation gives a significantly lower temperature of (48 ± 11) eV. The fitted abundances are about half solar values, in agreement with previous measurements. At higher energies, the spectrum does not require non-thermal components and the observation of a line at 6.8 keV supports the ASCA interpretation of the source as an accreting white dwarf. Assuming a source distance of 188 pc, the bolometric luminosity in the 2–10 keV band is 6×10^{32} ergs s⁻¹. Simultaneous optical measurements by the Wendelstein Observatory near Munich, indicate that the source continues to be in a late but rather normal Be phase, with no obvious signs of a transition to the Be-shell phase. The measured magnitudes at B, V and R wavelengths of 2.18 ± 0.06 , 2.23 ± 0.02 and 2.36 ± 0.03 , respectively, confirm this.

Key words: stars: individual: γ Cas – stars: emission-line, Be – stars: white dwarfs – X-rays: stars

1. Introduction

Gamma Cassiopeiae is a B0.5 IVe star which has been extensively studied at optical wavelengths. It is also a moderately strong X-ray source ($\sim 10^{33}$ erg s⁻¹) and is believed to form part of a binary system, based on its similarities to the Be X-ray binary, X Persei (Mason et al. 1976). However, despite two decades of intense study, its status as an X-ray binary remains unclear.

The phenomenological model of γ -Cas has been derived largely from optical interferometric and spectropolarimetric

measurements (e.g., Horaguchi et al. 1994; Stee et al. 1995; Quirrenbach et al. 1997). They reveal a pronounced mass loss from the system (which implies that material is available for accretion onto a companion) and the presence of a substantial circumstellar envelope, which in turn, may provide the source of material for a companion to accrete from (Vakili et al. 1994). The presence of a companion is inferred from the observed oscillations in the ratio of V/R peak intensities in double peaked H α line profiles. Additional evidence is provided by an analysis of a 20 ks EXOSAT observation by Frontera et al. (1987). In the 2–8 keV energy range, the observed X-ray flux is ~ 2 orders of magnitude greater than that expected for a star with spectral class earlier than A (Pallavicini et al. 1981) and the 2–20 keV spectrum is consistent with that commonly observed in low luminosity Be/neutron binary star systems. The derived spectral index is ~ 1.5 for a power-law interpretation, or alternately, a temperature of ~ 10 –15 keV for optically thin bremsstrahlung emission. A timing analysis of the data failed to shed any insight into the orbital dynamics of the system, but did suggest a possible period of ~ 100 mins. However, Parmar et al. (1997) found no evidence for this periodicity in a subsequent 30 hr continuous EXOSAT observation, suggesting instead that the apparent periodicity is produced by statistical fluctuations. In common with many other X-ray binaries, chaotic X-ray variability with no preferred timescale down to ~ 10 s has also been observed (Kubo et al. 1988) and is thought to arise from fluctuations in the rate of accretion onto the compact object.

1.1. Neutron star, white dwarf or coronal emission?

Its X-ray luminosity of 10^{33} ergs s⁻¹ is consistent with both coronal emission (as observed from OB stars) and wind powered emission from either a neutron star or white dwarf. However, the measured temperature of ~ 12 keV is much hotter than found in OB stars, which usually have temperatures in the range ~ 0.5 –2.5 keV. Evidence that the compact companion in the γ -Cas system is actually a white dwarf, rather than a neutron star, is strongly suggested by the *Tenma* observation of strong Fe line emission at 6.8 keV of equivalent width, EW, 280 eV (Murakami et al. 1986). This implies a highly ionized plasma of temperature, $kT \sim 10$ keV which is commonly seen in white

dwarf systems (Mukai & Shiokawa 1993). High mass neutron star accreting systems, on the other hand, usually show Fe emission at 6.4 keV, with occasionally weak ($EW < 100$ eV) emission at 6.7 keV. An 8.4 ks ROSAT PSPC observation of γ -Cas (Haberl 1995) revealed evidence for a soft component which can be modeled as black body radiation of $kT \sim 200$ eV. It is believed to emanate from the heated surface of a white dwarf near the magnetic pole. This component appears to be modulated with a period of 135.3 mins which may be the spin period of the white dwarf. The modulation may then arise from geometrical self occultation by the white dwarf (King & Shaviv 1984), or by photoelectric absorption, as in the accretion curtain model of Rosen et al. (1988). Based on a possible stellar modulation in the chaotic X-ray emission and a similarity (spectrally and temporally) to late-type flaring stars (such as RS CVns), Smith et al. (1998) proposed a mechanism in which X-rays are produced in magnetically generated hot spots on the surface of γ -Cas itself. Such an origin would be consistent with the apparent lack of orbital motion and the active Be nature of the star.

In this paper we report on simultaneous optical and X-ray measurements with the BeppoSAX satellite and present the first 0.1–50 keV broad-band energy spectrum of γ -Cas.

2. Optical observations

As γ -Cas was one of the first stars observed to display the characteristics nowadays categorized as Be star phenomenon, the collection of optical observations covers a very long time baseline (e.g., AFOEV 1998). Based on photometric and spectroscopic peculiarities in common with other Be stars, Doazan et al. (1983) describe a three phased “cycle” in the long term behavior of γ -Cas, without implying any periodicity. Such a cycle starts with the building-up of Balmer emission. This phase is characterized by moderate irregular variability in the Balmer line intensities as well as in the visual magnitude. The line intensities and magnitudes show a slow increase over several decades (Be phase). This behavior culminates in a second phase of high variability in both characteristics (Be-shell phase) lasting approximately 10 years, which was last observed in γ -Cas from 1932 to 1942. The cycle is terminated by a third phase with no detectable Be characteristics (B-normal phase) lasting about 5 years. The visual magnitude of γ -Cas has more or less continuously risen from its early Be phase value of about $2^m 6$ in 1950 to a present value of $\sim 2^m 2$.

Contemporaneous to the BeppoSAX observations, optical monitoring of γ -Cas was carried out with Universitäts-Sternwarte München’s 80 cm Telescope located at the Wendelstein Observatory. Measurements were made using the MONICA instrument in Johnson B, V and R around 01:50 UT on 1998, July 21. The measured magnitudes were: $B=2.18 \pm 0.06$, $V=2.23 \pm 0.02$ and $R=2.36 \pm 0.03$, which confirms the “normal” behavior of γ -Cas at this time. Moreover, the resulting $B-V = -0^m 05$ is in perfect agreement with a correlation between visual magnitude and B-V color index described by Horaguchi et al. (1994), which shows that, the brighter the V magnitude of γ -Cas, the redder it becomes in B-V. This trend is commonly

interpreted as being due to the growth of a circumstellar envelope with time. In summary, γ -Cas, as indicated by its visual observables, is currently in a late but rather normal Be phase, with no obvious signs of a transition to the spectacular Be-shell phase.

3. X-ray observations

The X-ray observation was carried out using the BeppoSAX astronomy satellite (Boella et al. 1997a). The platform contains four coaligned Narrow Field Instruments (NFI) providing broad-band coverage over the energy range 0.1 to 300 keV. The NFI are: the Low Energy and Medium Energy Concentrator Spectrometers (LECS and MECS), the High Pressure Gas Scintillation Proportional Counter (HPGSPC) and the Phoswich Detection System (PDS). The LECS covers the energy range 0.1–10 keV with an energy resolution of 8% at 6 keV (Parmar et al. 1997). The MECS consists of three detectors similar to the LECS, with identical energy resolution but with thicker entrance windows, spanning 1.3–10 keV (Boella et al. 1997b). The HPGSPC is sensitive over the energy range 4–120 keV with an energy resolution of 4% at 60 keV (Manzo et al. 1997). The PDS covers the high energy range 13–300 keV with an energy resolution of 15% at 60 keV (Frontera et al. 1997).

γ -Cas was observed from 1998 July 20 11:21 UTC to July 21 22:15 UTC, yielding total on-source exposure times of 10.2, 37.4, 20.0 and 18.6 ks in the LECS, MECS, HPGSPC and PDS, respectively.

3.1. Data analysis

Data were processed with the SAXDAS data analysis system using standard procedures. For the LECS and MECS, source events were extracted from regions of radii 8 and 4', respectively, centered on the source position. Spectral fitting was carried out using XSPEC (version 10.1). The LECS data were fit over the energy range 0.1 to 10 keV; the MECS 1.85 to 10 keV; the HPGSPC 7 to 65 keV and the PDS 13 to 200 keV. To ensure that the fitting statistic (χ^2) was unbiased across the entire energy range, data were rebinned to a width of 33% of the full width at half maximum energy resolution function of each instrument and also under the condition that each bin contained a minimum of 20 counts. It is known from inter-instrument spectral calibrations that there can be small position dependent normalization differences between the instruments. Therefore, these factors were included as free multiplicative parameters during multiple NFI spectral fitting.

4. X-ray results

4.1. Intensity variations

Fig. 1 shows low and high energy light curves measured by the MECS (1.3–10.0 keV) and the PDS (13–200 keV) after background subtraction. The time resolution is 400 s. The source intensity is clearly variable with a doubling of the flux occurring on the time scale of adjacent bins. The fastest observed

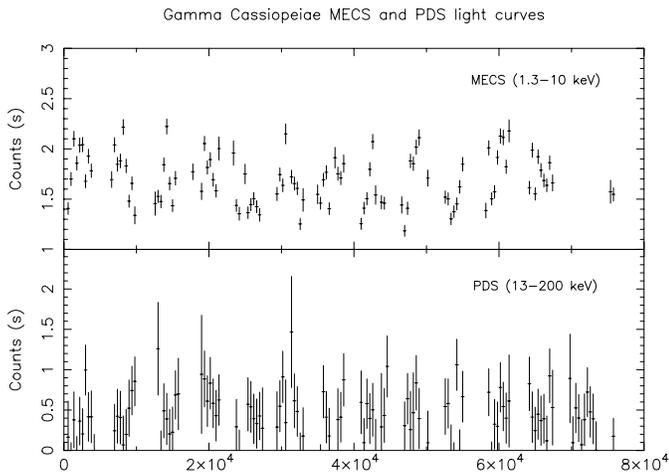


Fig. 1. The background subtracted 1.3–10 keV and 13–200 keV X-ray light curves of γ -Cas measured by the MECS and PDS. The data are binned in 400 s intervals. Considerable variability is apparent in the MECS, even down to time scales of 10 s when finer time resolution is used

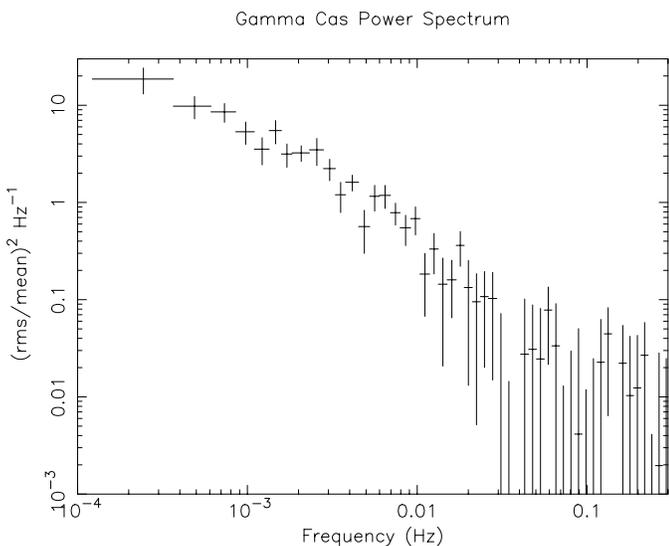


Fig. 2. The 1.3–10 keV power density spectrum of γ -Cas. The Nyquist frequency corresponds to 0.5 Hz

fluctuation in the MECS is on a time scale of ~ 10 s, consistent with the ASCA result of Kubo et al. (1998). In the PDS, the fastest observable variation is of the order of ~ 40 s. This time scale implies an upper limit on the size of the emission region of a few $\times 10^{11}$ cm. Next a search for periodic variations was carried out. On short time scales ($f \sim 10^{-4}$ –0.5 Hz), a power density curve reveals a $1/f$ -type distribution, but no clear periodicities (see Fig. 2). At much longer periods, a period search reveals weak enhancements at 35 and 145 mins. We estimate that for narrow QPO/periodicities in the 0.01 Hz to 0.1 Hz range, we could detect a 10% amplitude modulation at the 3σ level.

In order to study the long-term X-ray variability of γ -Cas, we have also analyzed R-XTE All Sky Monitor (ASM) data which has continuously observed the source from 1996 Febru-

ary, 20 to 1998 December, 31. We have searched for periods in the range 30–500 days using the Lomb-Scargle periodogram, using both the individual dwell and 1-day averages data. No peaks with a high significance (i.e., $>99\%$) were found in the individual dwell data, although one peak at a period of ~ 200 days was of marginal significance (at the $\sim 90\%$ level). As a check on its reality, we replaced the R-XTE ASM measurements with data drawn from a Gaussian distribution centered on zero with a σ of 1 (i.e. no signal). We note that the peak still existed (albeit with a much lower significance), implying that it is probably caused by a windowing effect and therefore does not reflect a true period in the X-ray flux of γ -Cas. Analysis of the 1-day averaged data yielded similar results, i.e., no significant periodicities. We estimate that for periods around 100 days, we would have detected a 10% periodic modulation at the 90% confidence level.

4.2. Spectral variations

Simple models (i.e., power-laws, bremsstrahlung, etc.) gave poor fits to the data. For example, an absorbed power-law gives a χ^2 of 684 for 203 degrees of freedom (dof). The addition of an iron line at 6.77 ± 0.03 keV improves the fit significantly ($\chi^2/\text{dof} = 505/200$), but is still unacceptable at energies above 10 keV. Based on previous ROSAT and ASCA measurements (Haberl 1995; Kubo et al. 1998), we next investigated optically thin thermal plasma models with both the temperature and elemental abundance as free parameters. The results are listed in Table 1. A best-fit MEKAL model, based in the calculations of Mewe and Kaastra (Mewe et al. 1986; Kaastra 1992) yields a χ^2/dof of 266/202 for a fitted temperature of 12.5 ± 0.7 keV and an abundance of 0.43 ± 0.05 . These values are in agreement with the ASCA values of 10.7 ± 0.6 keV and 0.35 ± 0.08 (Kubo et al. 1998). The fit shows significant residuals around 300 eV and 1 keV. The addition of a carbon line at 277 eV results in a better fit ($\chi^2/\text{dof} = 244/199$), which is significant under an F test ($P > 99.9\%$). If real, this could imply an overabundance of carbon. Following the ROSAT observation of a soft component, we next added a blackbody component. This resulted in a slightly worse fit ($\chi^2/\text{dof} = 248/201$) primarily due to residuals around 0.3 keV. The fitted temperature was $100 \pm_{13}^{320}$ eV, which is consistent with the ROSAT value of 200 ± 10 eV (Haberl 1995). Assuming that the source is best described in terms of a multi-temperature plasma, we replaced the blackbody component with a second, lower temperature, MEKAL component. The resulting χ^2/dof is 240/200 for temperatures of 12.3 ± 0.6 keV and 0.05 ± 0.01 keV. The fitted abundance is 0.423 ± 0.06 , consistent with previous measurements. Whereas ROSAT reported marked variability in the soft component and suggested a possible modulation period of 135 mins, our data are consistent with a constant mean rate throughout the observation. For example, in the 0.1 to 0.5 keV band, a best-fit constant mean rate yields a χ^2/dof of 64/57, as compared to 423/64 for the 0.1–10 keV band. The combined NFI count spectrum and the best-fit two-temperature MEKAL model (folded through the appropriate instruments response functions) is shown in Fig. 3. In Fig. 4 we show the cor-

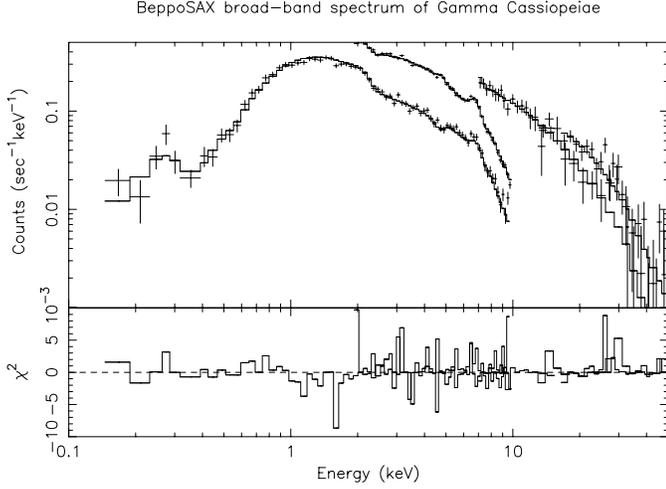


Fig. 3. The BeppoSAX spectrum of γ -Cas measured by the NFI. The solid lines show the best-fit 2 component optically-thin thermal plasma (MEKAL) model (see text), folded through the instrumental responses. The contribution to χ^2 are shown in the lower panel

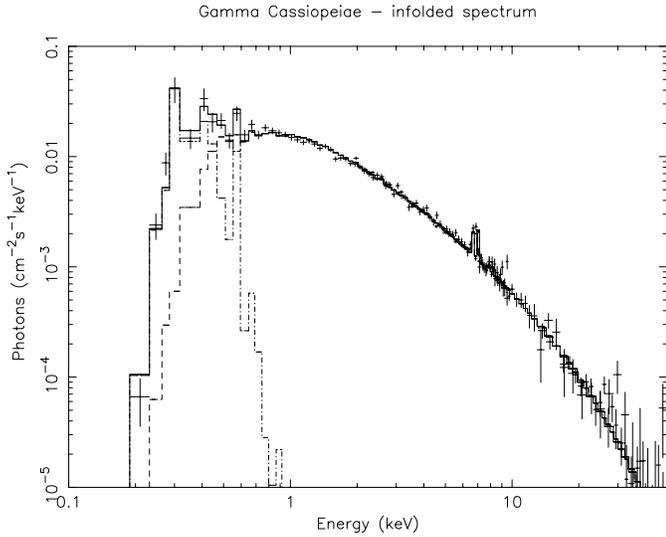


Fig. 4. The best-fit incident photon spectrum of γ -Cas based on an absorbed two temperature MEKAL model. The individual contributions are shown separately as long and short dashed lines

responding best-fit incident photon spectrum. The observed flux in the 2–10 keV band is $1.33 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, which for a source distance of 188 pc (ESA 1997), corresponds to a bolometric luminosity of $5.7 \times 10^{32} \text{ erg s}^{-1}$.

5. Discussion

The comparison of BeppoSAX results with previous results can be misleading in view of the limited energy range of early missions – meaning that the results can be critically dependent on assumed emission models which may be inappropriate for the wide bandwidth of BeppoSAX. For example, ASCA data are perfectly consistent with a power-law continuum whereas BeppoSAX data are not, when energies above the ASCA upper en-

Table 1. Best-fit spectral parameters. Uncertainties are given at the 90% confidence level for one interesting parameter. Line energies, widths and temperatures are in units of keV. Line fluxes and model fluxes are given in units of photon $\text{cm}^{-2} \text{ s}^{-1}$ and $10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively. Column densities, N_{H} , are in units of $10^{21} \text{ atom cm}^{-2}$ and equivalent widths, EW, in units of eV

Parameter	Value
<i>Model 1: Absorbed power-law plus Fe line</i>	
N_{H}	2.75 ± 0.20
α	$1.69 \pm_{0.02}^{0.03}$
E_{line}	6.77 ± 0.05
σ_{line}	0.21 ± 0.07
EW	296 ± 48
$\text{Flux}_{\text{line}}$	$(3.8 \pm 0.6) \times 10^{-4}$
Model flux (2–10 keV)	1.29
χ^2/dof	505/200
<i>Model 2: Absorbed MEKAL</i>	
N_{H}	1.55 ± 0.09
kT	12.5 ± 0.4
Abundances	0.43 ± 0.05
Model flux (2–10 keV)	1.33
χ^2/dof	266/202
<i>Model 3: Absorbed MEKAL plus C line</i>	
N_{H}	1.63 ± 0.1
kT	12.4 ± 0.6
Abundances	0.42 ± 0.05
$\text{Flux}_{\text{line}}$	$0.35 \pm_{0.14}^{0.25}$
σ_{line}	< 0.02
EW	3220 ± 1800
Model flux (2–10 keV)	1.33
χ^2/dof	243/199
<i>Model 4: Absorbed 2 component MEKAL</i>	
N_{H}	1.7 ± 0.15
kT ₁	12.3 ± 0.6
kT ₂	0.05 ± 0.01
Abundances	0.42 ± 0.05
Model flux (2–10 keV)	1.33
χ^2/dof	240/200

ergy threshold are taken into account. Globally, the BeppoSAX data show that the γ -Cas spectrum is consistent with an optically thin thermal plasma distribution which does not require non-thermal components – as might be expected for accreting neutron star models. The Fe line is a persistent feature of this source and is generally attributed to a blend of Fe XXV (6.7 keV) line emission and Fe XXVI (6.97 keV) emission produced in a highly ionized, optically thin thermal plasma. The implied temperature of ~ 12 keV is perfectly consistent with that derived independently for the continuum. Such emission is most consistent with white dwarf scenarios. High mass neutron star systems, on the other hand, generally have strong emission at 6.4 keV and only weak, if any, emission at 6.7 keV. Also, such systems generally have non-thermal spectra which are well described by a power-law distribution with a high energy cut-off

and may be expected to produce cyclotron line emission above ~ 10 keV. None of these are observed by BeppoSAX.

Until recently, the main problem with degenerate dwarf models has been reproducing the relatively high luminosity. However, this has been substantially relaxed in view of the recently revised source distance of 188 pc (ESA 1997) as opposed to the previously assumed value of 250 pc. When coupled with a re-evaluation of wind parameters by Stee et al. (1995), the observed luminosity is no longer in conflict with current limits on the orbital motion. The lack of X-ray pulsations may indicate that the white dwarf does not possess a strong magnetic field or that the orbital period is long compared to the time-line of the current X-ray database. The latter explanation would be consistent with the calculations of Kubo et al. (1998) who derive an orbital period for the system of 150 days. Lastly, in a critical review of X-ray emission models, Kubo et al. (1998) conclude there is no compelling evidence for the coronal model of Smith et al. (1998) since the very properties they claim are characteristic of coronal emission are also seen in the dwarf nova SS Cyg (Watson et al. 1985).

In summary, our results confirm previous ASCA and ROSAT measurements and support the view of Kubo et al. (1998) that the characteristics of the X-ray emission are fully consistent with the conventional picture of γ -Cas as a binary system containing an accreting non-magnetic white dwarf, rather than neutron star binary or coronal emission models.

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available on line, at <http://astro.estec.esa.nl/Hipparcos/catalog.html>. The quick-look RXTE ASM data were provided by the ASM/RXTE team (<http://space.mit.edu/XTE/asmlc>). This research has made use of the AFOEV database, operated at CDS, France (<http://astro.u-strasbg.fr/afoev>).

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