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Luminosity dependent changes in the X-ray pulse profile of the transient pulsar Cepheus X-4 during its declining phase of the 1997 outburst

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Abstract. The transient X-ray pulsar Cepheus X-4 underwent its latest outburst in 1997, during July–August, which lasted for about 30 days. The Pointed mode Proportional Counters (PPCs) of the Indian X-ray Astronomy Experiment (IXAE) on board IRS-P3 satellite observed the source in its declining phase during 1997 July 28 to July 30. The timing analysis of the data confirms the 66 seconds pulsation of the neutron star. The X-ray pulse profile obtained in two energy bands between 2 and 18 keV, shows energy dependent variations. The pulse profile obtained by us in the declining phase of the outburst when the X-ray luminosity of the source was about 6×10^{35} ergs s^{-1}, is distinctly different from the one observed with the RXTE in the earlier phase of the outburst. It is found that near the end of the outburst, the relative strength of the two pulses of the double-pulse profile got reversed and the inter-pulse became more dominant compared to the main pulse. The observations can be interpreted in terms of a luminosity dependent emission profile of the pulsar, where depending on the pulsar geometry with respect to line of sight, one of the emission patterns, either a pencil-beam or a fan-beam, becomes more dominant. This is due to the changes in the pulsar magneto-sphere below a specific luminosity, which may cause relative changes in accretion process onto the two poles of the neutron star.

Key words: accretion, accretion disks – X-rays: stars – stars: pulsars: individual: Cep X-4

1. Introduction

Cepheus X-4 was discovered in 1973 as a transient X-ray source by the OSO-7 satellite (Ulmer et al. 1973; Markert et al. 1973). X-ray pulsations in the source were discovered (Makino et al. 1988; Koyama et al. 1991) in 1988 March, by the GINGA satellite, during its outburst which lasted for about 30 days reaching a peak intensity of 100 mCrab. The X-ray pulse period was found to be 66.2490 ± 0.0001 seconds and the ratio of the period derivative and the period $\dot{P}$/P of the pulsar was found to be -2×10^{-3} yr^{-1}. The X-ray pulse profile showed significant energy dependence.

Another outburst in Cepheus X-4 (Cep X-4) was identified by ROSAT in 1993 June (Schulz et al. 1995). The pulsar was observed in two extreme intensity states, during an outburst and also in a quiescent state in which source flux was lower by a factor of 16. The X-ray pulsation period during the outburst was found to be 66.2552 ± 0.0007 seconds. In contrast to the GINGA results, the source showed a spin-down episode between the two outbursts with $\dot{P}$/P of +1.8x10^{-5} yr^{-1}. The pulse profile between 0.1 and 2.5 keV showed energy dependence.

The BATSE (Fishman et al. 1989; Horack 1991) on board Compton Gamma-Ray Observatory detected the two outburst of Cep X-4, the outburst of 1993 and its latest outburst of 1997 (Wilson et al. 1999). The results obtained from these outbursts indicated that the transient pulsar is in the spin-down phase with a period P = 66.2770 seconds (MJD 50,641) and $\dot{P}$/P of +9×10^{-5} yr^{-1}. The X-ray pulse profile obtained at various energies in 2–30 keV range from RXTE data showed energy and intensity dependent variations (Wilson et al. 1999).

The All Sky Monitor (ASM) of Rossi X-ray Timing Explorer (RXTE) also detected the latest X-ray outburst of Cepheus X-4 in 1997 July which lasted for 30 days starting at epoch MJD 50,630. The one day average light curve is shown in Fig. 1. The peak intensity of the latest outburst is about 45 mCrab which is almost half the peak intensity of the outbursts observed earlier. However its duration of about a month, is similar to that of the three earlier outbursts. Out of two classes of outburst activity observed in the Be binary systems (Bildsten et al. 1997), the outburst of Cep X-4 could be associated with the Class I activity due to its long duration of 30 days without any appreciable change in the pulse period during its outburst phase. Class I type activity pertains to periodically occurring outbursts associated with the periastron passage of the neutron star while Class II is irregular transient activity, with higher luminosity and outburst occuring at arbitrary orbital phase. Large and steady change in the spin-up rates are observed due to formation of transient accretion disks during the class II outburst activity in many

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Send offprint requests to: K. Mukerjee (kmukerji@tifr.res.in) transient Be/binary systems (Kriss et al. 1983; Stella et al. 1986; Motch et al. 1991).

Applying the relationship of Corbet (1984) between the spin and orbital periods in the Be binary pulsars, a minimum limit of 100 days is estimated for the orbital period of Cep X-4 from GINGA observations (Koyama et al. 1991). The corresponding mass of the companion star was found to be greater than 10 $M_\odot$ for a 1.4 $M_\odot$ neutron star. These estimates of mass of the companion star, large orbital and spin periods and recurrent transient nature of Cep X-4 are consistent with the general properties of a Be binary system. Recent optical observations have confirmed the Cep X-4 system to be a Be /X-ray binary (Bonnet-Bidaud & Mouchet 1997). If Cep X-4 is a Be binary, as inferred from the optical observations, such outburst should be recurrent and periodic due to periastron passage of the neutron star through the Be star disk. The long term ASM light curve may, therefore, reveal many interesting details about the nature of outbursts and also provide information about the orbital parameters of the Be binary system.

In this paper, we report a detailed study of the 2–18 keV pulse profile obtained during the later part of the decay phase of the latest 30 days outburst of Cep X-4. The Indian X-ray Astronomy Experiment (IXAE) observations carried out for 3 consecutive days were made after the RXTE observations. The double-peak pulse profile obtained in the later part of the decay of the outburst, when the source luminosity decreased to about 6×10^{35} ergs s^{-1}, is found to be inter-pulse dominated compared to the main-peak dominated double-pulse profile observed by BATSE and RXTE. The observations of IXAE thus provide additional opportunity to study the luminosity dependence of pulse profile of the source.

2. Observations

The X-ray observations were carried out with the Pointed Proportional Counters (PPCs) of the Indian X-ray Astronomy Experiment (IXAE) on board the IRS-P3 satellite. The complete instrument and operational details are described in Agrawal et al. (1997) and Agrawal (1998). The three identical PPCs sensitive in the energy range of 2 to 18 keV, have a total effective area of 1200 cm^2 and a field of view of 2.3^o by 2.3^o FWHM. The PPCs can be operated in one of its many operational modes i.e., fast, medium, nominal, slow or pulsar mode. Cep X-4 was observed by the PPCs in the nominal mode in which counts are sampled with 1.02 second integration.

The outburst of July 1997 was observed by three satellite borne experiments consecutively. BATSE observed the source in the initial rising phase of the outburst during July 3–15 followed by PCA of RXTE on July 18 (source flux $\approx$ 23 mCrab) and again on July 25 (source flux $\approx$ 8 mCrab). The IXAE observations were made during July 28–30 (MJD 50,658-50,660) when source flux had decreased to about 4 mCrab, yielded 12000 s of useful data. The PPCs recorded about 5.6 cts. s^{-1} on an average during the IXAE observations. Assuming a distance of 3.8$\pm$0.6 kpc (Bonnet-Bidaud & Mouchet 1997) and the spectral shape given in Koyama et al. (1991) a luminosity of 4.4×10^{35} ergs s^{-1} in the 2–18 keV band or 6.2×10^{35} ergs s^{-1} in 0.1–100 keV band is estimated. The IXAE and the RXTE observations were made in the declining phase of the outburst. Data obtained with the PCA on-board the RXTE at two different epochs July 18 and July 25 were used for comparison.

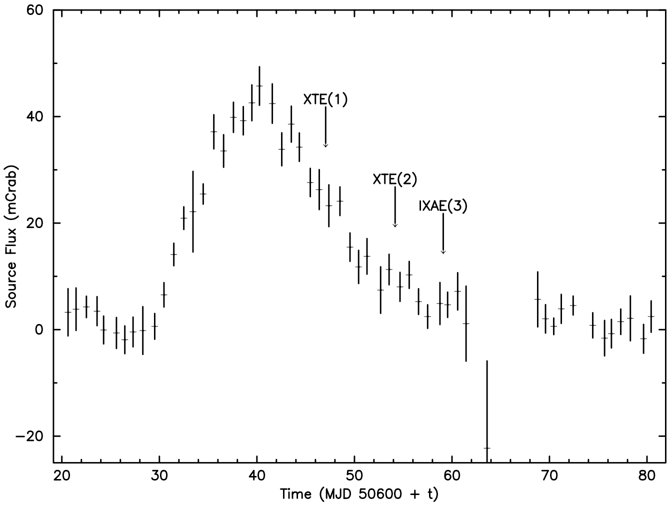

Fig. 1. Outburst profile of Cep X-4 observed during 1997 July-August by ASM of RXTE. The RXTE and IXAE mean observation epochs are marked as XTE(1), XTE(2) and IXAE(3) respectively. The verticle lines on data points denote errors at 1σ level.

Table 1. Pulse period history of Cepheus X-4

Observation Year	Satellite	MJD	Pulse Period	Ref[b]
1988 April	GINGA	47263.5	66.2490 ± 0.0001	[1]
1993 June	ROSAT	49160.0	66.2552 ± 0.0007	[2]
1997 July	BATSE	50633.0	66.2712 ± 0.0017	[3]
		50635.0	66.2730 ± 0.0017	
		50637.0	66.2748 ± 0.0017	
		50639.0	66.2743 ± 0.0017	
		50641.0	66.2765 ± 0.0017	
		50641.0	66.2775 ± 0.0017	
1997 July	RXTE	50647.05	66.277 ± 0.017	[3]
		50654.17	66.273 ± 0.017	
1997 July	IXAE	50658.12	66.27[a] ± 0.04	[4]
		50659.11		
		50660.10		

[a] average of three days of IXAE observations.
[b] *References* [1] Koyama et al. (1991) [2] Schulz et al. (1995) [3] Wilson et al. (1999) [4] Present Work

3. Analysis and results

The PPCs record the data in individual memories along with the timing and house keeping information. In nominal-mode of operation of the PPCs, data were acquired for about 15 to 20

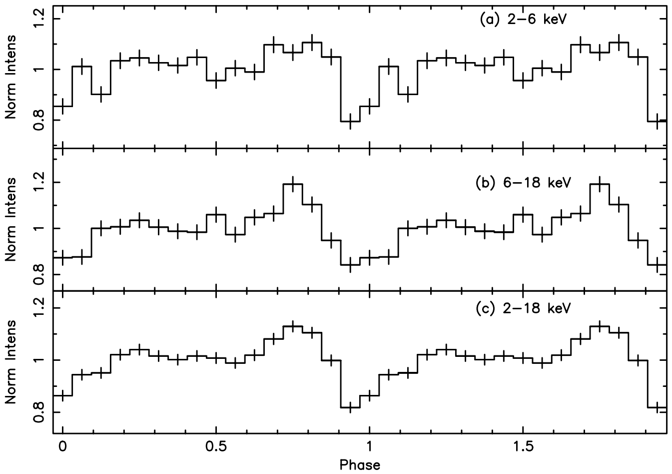

Fig. 2a–c. Average pulse profiles of Cep X-4 at three different energy bands obtained from IXAE data while source intensity reduced to 4 mCrab; **a** 2–6 keV **b** 6–18 keV and **c** 2–18 keV. The errors on the data points are derived from counting statistics at 1σ level.

minutes for five consecutive orbits in a day. Therefore, for each PPC there are 5 stretches of binned data for each day of observation. Time corrections were applied and background subtractions were carried out prior to adding the three PPC data files. The relevant data were accumulated in three energy bands i.e. 2 to 6 keV, 6 to 18 keV and the summed 2 to 18 keV band. The epoch folding technique was used to search for pulsations with period around 66 s and a pulse period of 66.27 ± 0.04 s was obtained. The uncertainty in the pulse period corresponds to 1σ level and was calculated using the technique described in Leahy (1987). The IXAE period is consistent with the pulse period of 66.27 ± 0.02 s obtained from the RXTE data (Wilson et al. 1999). These observations imply spin-down of the pulsar when one compares the periods measured during the earlier outbursts. A summary of all the pulse period measurements of Cep X-4 available so far is given in Table 1.

The X-ray pulse profiles of Cep X-4 from the IXAE observations were obtained by combining all the data from three days of observations. These are shown in Fig. 2 in 2–6 keV, 6–18 keV and 2–18 keV bands. There is an indication of energy dependent variability in the pulse shape. The X-ray pulse profiles obtained from the two RXTE observations are shown in Fig. 3 for comparison. Both the profiles show a double-pulse shape but in the IXAE pulse profile, the inter-pulse is dominant over the main-pulse.

The RMS pulse fractions estimated from the RXTE and the IXAE profiles are tabulated in Table 2 in three energy bands with decreasing source flux for comparison. Variation of the RMS pulse fractions as a function of energy, obtained from the RXTE (Wilson et al. 1999) and the IXAE data, is shown in Fig. 4. The errors in the data reported are shown by vertical lines and are contained in the symbol used. There is an indication that the pulse fraction decreases with decrease in the source intensity. It can also be noted from Fig. 4, that energy above which the pulse fraction starts dropping, shifts progressively towards lower values as the source luminosity decreases as evident from the RXTE data. The pulse fraction obtained from the IXAE observations at much lower luminosity shows no statistically significant variation with energy.

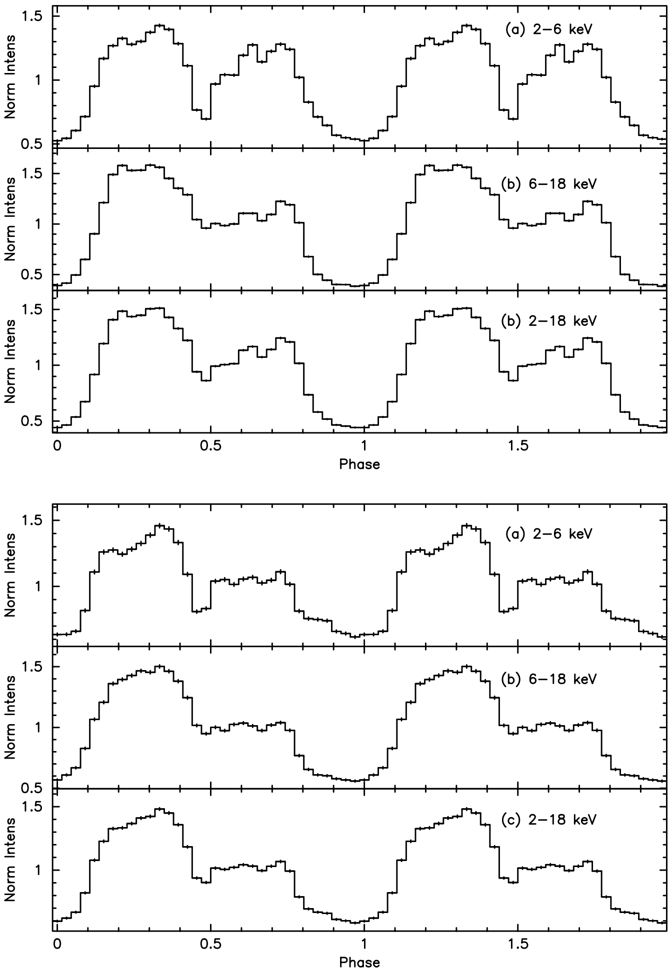

Fig. 3. Comparison pulse profile of Cep X-4 at different intensity of source during the decline phase of the 1997 outburst; Top pannel shows RXTE profile of MJD 50,647 when the source intensity was 23 mCrab and bottom pannel shows RXTE profile on MJD 50,654 when the source intensity was about 8 mCrab. The error bars derived from counting statistics are 1σ confidence limits.

Table 2. RMS Pulse Fraction(RPF) comparison of Cep X-4

MJD	I	RPF(%) 2–6 keV	RPF(%) 6–18 keV	RPF(% 2–18 keV
50647.05	23	33.56 ± 0.44	43.55 ± 0.30	39.47 ± 0.25
50654.17	8	27.06 ± 0.78	31.19 ± 0.59	29.42 ± 0.47
50659.11	4	14.52 ± 2.05	11.19 ± 2.26	12.85 ± 0.69

I denotes source intensity in mCrab.

4. Discussion

The following important features were noticed during the observations of Cep X-4 with the IXAE. We have observed a decrease

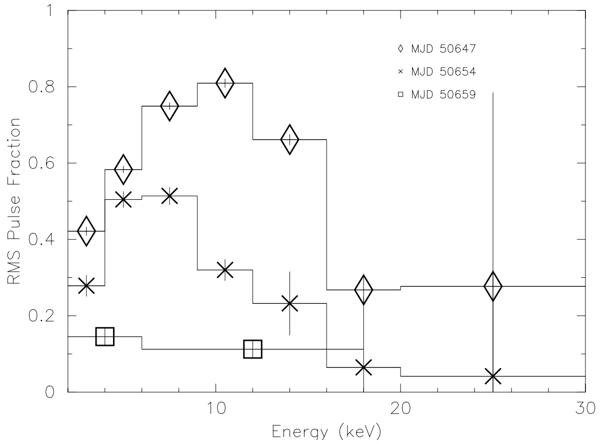

Fig. 4. RMS pulse fraction measurements in different energy bands between 2–30 keV from two RXTE observations on **a** MJD 50,647 **b** MJD 50,654 (adapted from Wilson et al. 1999) and **c** The IXAE observations on MJD 50,658–50,660 during the decay of the 1997 outburst of Cep X-4. The errors on data points are represented by vertical line with confidence limit of 1σ.

in the pulse fraction in Cep X-4 with luminosity as it was seen in other pulsars. The pulse profiles obtained with the IXAE show some evidence of energy dependence like the one also observed with the RXTE. A remarkable change in the pulse-profile of Cep X-4 was observed with change in the source luminosity. The main-pulse dominated double pulse changed to inter-pulse dominated double pulse profile when the luminosity was 6×10^{35} $\mathrm{ergs\,s^{-1}}$. These features are discussed here in detail.

The phenomenon of decrease in X-ray pulse fraction when the source flux drops below a certain threshold, has been observed in other X-ray pulsars like GX 1+4 and GRO J1744-28 and it has been interpreted as due to the “Propeller effect” (Cui 1997). We show here that the decrease in the pulse fraction in Cep X-4 is not due to such an effect.

The minimum luminosity $\mathrm{L_X}$(min) at which an X-ray pulsar turns off due to the centrifugal inhibition of accretion, the Propeller effect is given by (Illarionov & Sunyaev 1975)

$$\begin{aligned}\mathrm{L_X(min)} \;\approx\; & 2{\times}10^{37}(\mathrm{R}/10^{6}\,\mathrm{cm})^{-1}(\mathrm{M}/1.4\,\mathrm{M_\odot})^{-2/3} \\ & \times(\mu/10^{30}\ \mathrm{G\,cm^{3}})^{2}(\mathrm{P_s}/1\ \mathrm{s})^{-7/3}\,\mathrm{ergs\,s^{-1}}\end{aligned}$$

Where R, M, μ and $\mathrm{P_s}$ are radius, mass, magnetic moment and spin period of the neutron star respectively. For a dipole-like field configuration μ = B× R^3, where B is the surface polar magnetic field strength. Using B = 2.6×10^{12} G (Mihara et al. 1991) and R = 10^6 cm, one obtains $\mu = 2.6\times10^{30}\ \mathrm{G\,cm^3}$.

With this value of μ, $\mathrm{P_s}$ = 66.27 s and M = 1.4 $\mathrm{M_\odot}$, one obtains minimum luminosity below which the “propeller effect” will set in Cep X-4 as

$$\mathrm{L_X(min)} = 7.6{\times}10^{33}\,\mathrm{ergs\,s^{-1}}$$

The Cep X-4 luminosity during the IXAE observation is estimated to be 6.2×10^{35} $\mathrm{ergs\,s^{-1}}$. It is therefore inferred that the accretion process was active during our observation period while the outburst was gradually decaying. From Table 2, it can be seen that when the source is bright, decrease of luminosity by a factor of 3 results in a change in pulse fraction by a factor of 1.3. At lower luminosity, however the change in pulse fraction is larger, by a factor of 2 or more, with change in luminosity by a factor of 2. This is indicative of a sudden change in pulse fraction at lower luminosity. Since decrease in pulse fraction with luminosity is not due to propeller effect, the most probable reason for this change could be due to different mode of accretion occuring below a critical luminosity.

Appreciable plasma entry by any mode (Elsner & Lamb 1984) produces copious emission of X-rays from the stellar surface. The fate of the plasma approaching the magnetosphere depends on how the luminosity of the star compares to a critical luminosity $\mathrm{L_{crit}}$ given by

$$\mathrm{L_{crit}} \equiv 2.0\times10^{36}\mu_{30}^{1/4}(\mathrm{M/M_\odot})^{1/2}\mathrm{R}_6^{-1/8}\,\mathrm{ergs\,s^{-1}}.$$

This luminosity defines a corresponding critical mass accretion rate.

$$\dot{\mathrm{M}}_{\mathrm{crit}} \equiv 1.5\times10^{16}\mu_{30}^{1/4}(\mathrm{M/M_\odot})^{-1/2}\mathrm{R}_6^{7/8}\,\mathrm{g\,s^{-1}}$$

The critical luminosity thus estimated for Cep X-4 is found to be $\mathrm{L_{crit}}$ = 3× 10^{36} ergs s^{-1} and critical mass accretion rate is estimated to be $\dot{M}_{\mathrm{crit}}$ = 1.6×10^{16} g s^{-1}.

Since the observed luminosity (6.2×10^{35}) during the IXAE observations is almost a factor 4 less than the critical value, it is possible that there are additional modes of accretion at the observed luminosity (Elsner & Lamb 1977;1984). These additional entry modes of plasma could enhance unpulsed (dc) component of the emission, with the result that the pulse fraction may decrease to the observed levels.

From the pulse shape observed in the two energy bands from the IXAE observations there is a suggestion of distinct two pulses at low energy which seem to merge in higher energy band. Moreover, the inter pulse at higher energy band appears more assymetric and sharper. Since these features are similar to those seen in the RXTE profiles, model described by Wilson et al. (1999) may be applicable to the IXAE profiles.

Complex changes in the pulse profile with luminosity have been seen in other X-ray pulsars such as GX 1+4 (Paul et al. 1997) and EXO 2030+375 (Parmar et al. 1989). The phenomenon observed here, namely, the change in the pulse profile with decrease in luminosity bears a close resemblance to that seen in EXO 2030+375 (Parmar et al. 1989). A geometrical model was applied by Parmar et al. (1989) to describe the pulse shape during the outburst activity of EXO 2030+375. The parameter values established with decreasing luminosity indicate that around a luminosity of 4×10^{36} $\mathrm{ergs\,s^{-1}}$, the pencil-beam becomes dominant compared to the fan-beam along with increase in the unpulsed (dc) component. Moreover, the relative intensity of total emission emanating from two poles get reversed, that is, total emission from one pole become much stronger compared to the other pole. Since EXO 2030+375 has magnetic dipole moment similar to that of Cep X-4 (Reynolds et al. 1993), one can treat $\mathrm{L_{crit}}$ same as estimated above. The change in the pulse shape observed for Cep X-4 during the IXAE observation can possibly be explained qualitatively along similar lines. During the decay of the outburst at a luminosity of 6×10^{35} ergs s^{-1} (which is less than the $\mathrm{L}_{\mathrm{crit}}$), the source shows a decrease in pulse fraction and an increase in the strength of the inter-pulse. These changes could be explained by an increase in the dc component, stronger pencil-beam and pole reversal, as seen in the case of EXO 2030+375.

This is compatible with the accretion scenario described by Elsner & Lamb (1977;1984). At a luminosity below the critical luminosity as estimated above, additional modes of accretion may be possible. These entry modes of plasma under certain conditions, may affect the change in the beam configuration to pencil-beam dominant emission with increase in the unpulsed (dc) part of its total emission. The observed decrease in the pulse fraction could be due to an increase in the unpulsed (dc) component of the total emission. Although observations of EXO 2030+375 (Parmar et al. 1989) also showed similar changes in the profile close to the critical luminosity, more observations during the decay phase of such outbursts are required to confirm this scenario, which may lead to a deeper understanding of the accretion process at lower luminosity.

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References

Agrawal P.C., 1998, Proc. of Int. Colloq. on perspectives of high energy astron. and astrophy., Universities Press Hyderabad, India, 408.
Agrawal P.C., Paul B., Rao A. R., et al., 1997, Journal of Korean Astronomical Society 29, S219
Bildsten L., Chakraborty D., Chiu J., et al., 1997, ApJ 113, 367
Bonnet-Bidaud J.M., Mouchet M., 1997 IAU Circ. 6724
Corbet R.H.D., 1984, A&A 141, 91
Cui W., 1997, ApJ 482, L163
Elsner R.F., Lamb F.K., 1977, ApJ 215, 897
Elsner R.F., Lamb F.K., 1984, ApJ 278, 326
Fishman G.J., Meegan C. A., Wilson R. B., et al., 1989, in Proc. of the GRO Science Workshop, ed. W. N. Johnson, (Greenbelt: NASA/GSFC), 2–39
Horack J. M., 1991, Development of the Burst and Transient Source Experiment(BATSE), Washington: NASA Ref. Pub. 1268)
Illarionov A.F., Sunyaev R.A., 1975, A&A 39, 185
Koyama K., Kawada M., Tawara Y., 1991, ApJ 366, L19
Kriss G.A., Cominsky L.R., Remillard R.A., Williams G., Thorstensen J. R., 1983, ApJ 266, 806
Leahy D.A., 1987, A&A 180, 275
Makino F. & GINGA team, 1988, IAU Circ. No. 4577
Markert T.H., Clark G.W., Hearn D.R., et al., 1973, IAU Circ., No. 4575
Mihara T., Makishima K., Kamijo S., Ohashi T., 1991, ApJ 379, L61
Motch C., Stella L., Janot-Pacheco E., Mouchet M., 1991, ApJ 369, 490
Parmar A.N., White N.E., Stella L., 1989, ApJ 338, 373
Paul B., Agrawal P.C., Rao A.R., Manchanda R.K., 1997, A&A 319, 507
Reynolds A. P., Parmar A.N., White N.E., 1993, ApJ 414, 302
Schulz N.S., Kahabka P., Zinnecker H., 1995, ApJ 295, 413
Stella L., White N. E., Ronsner R., 1986, ApJ 308, 669
Ulmer M.P., Baity W.A., Wheatom W.A., Peterson L.E., 1973, ApJ 184, L117
Wilson C.A., Finger M.H., Scott D.M., 1999, ApJ 511, 367