Astron. Astrophys. 364, 165–169 (2000)

ASTRONOMY AND ASTROPHYSICS

VHE gamma ray observations of Centaurus X-3

P.M. Chadwick, M.K. Daniel, K. Lyons, T.J.L. McComb, J.M. McKenny, S.J. Nolan, K.J. Orford, J.L. Osborne, S.M. Rayner, and K.E. Turver

Department of Physics, Rochester Building, Science Laboratories, University of Durham, Durham, DH1 3LE, UK

Received 8 May 2000 / Accepted 4 August 2000

Abstract. Further observations, using the University of Durham Mark 6 imaging telescope, have been made of the X-ray binary Cen X-3, which has been previously reported as a very high energy (VHE) gamma ray emitter. The results of these observations are reported and show that VHE gamma rays are emitted in all epochs when we have observed this object. No modulation of the VHE emission is seen, at either the pulsar or orbital period. Models of VHE emission from X-ray binaries are assessed in the light of these observations.

Key words: stars: individual: Cen X-3 – gamma rays: observations

1. Introduction

The accreting high-mass X-ray binary (HMXRB) Cen X-3 is an accurately measured system containing a 4.8 s pulsar in a 2.1 d orbit around an O-type supergiant. It has been extensively sudied since its discovery and is one of the best characterised HMXRBs. The orbit has been well enough determined to lead to mass estimates of both the neutron star and the companion (Hutchings et al. 1979) and its distance is well known (Krzemińsky 1974; Hutchings et al. 1979). Observations of a cyclotron line have enabled the surface magnetic field to be determined (Santangelo et al. 1998; Burderi et al. 2000).

The temporal behaviour of Cen X-3 is complex. The 4.8 s pulsar and 2.1 d orbital periods are reasonably well understood. Over the 20 years of X-ray observations, the spin period shows a secular spin up trend on which fluctuations with time scales of a few years and shorter are superimposed (Tsunemi et al. 1996). The orbital period shows a long-term decay thought to be due to tidal dissipation (Nagase et al. 1992). The object has long-term variations in X-ray intensity, exhibiting X-ray high and low states on timescales of ~ 150 d with no evidence for long term periodicity (Priedhorsky & Terrell 1983). Recently evidence has been found for kHz fluctuations in the X-ray intensity which have been interpreted as evidence for photon bubble oscillations (Jernigan et al. 2000).

Very high energy (VHE) gamma rays from Cen X-3 were first reported by the Durham group using earlier non-imaging telescopes (Carramiñana et al. 1989; Brazier et al. 1990) and by the Potchefstroom group (North et al. 1990; North et al. 1991). These early observations, which were considerably less sensitive than observations using imaging telescopes, showed evidence for sporadic outbursts of emission pulsed at the pulsar period in the > 1 TeV band. These observations hinted at emission at a preferred orbital phase but were not sensitive to weak unpulsed emission. There was some evidence that the emission was not from the site of the neutron star (Bowden et al. 1993). In a recent paper, Raubenheimer & Smit (1997) have reviewed the archival evidence and have concluded that there is evidence for VHE gamma ray emission from a site in the accretion disk trailing the neutron star by $70°$.

Observations with the Mark 6 imaging telescope have shown evidence for a weak unpulsed signal from Cen X-3 at energies > 400 GeV during observations in 1997 March and June (Chadwick et al. 1998). No episodes of pulsed emission were seen in these VHE signals.

EGRET observations of Cen X-3 have revealed one episode of sporadic emission in the 30 MeV – 10 GeV region (Vestrand et al. 1997). This emission observed during 1994 October was consistent with the gamma rays being pulsed at the contemporaneous pulsar period as deduced from BATSE X-ray measurements. No emission was detected during any other viewing period when EGRET observed Cen X-3.

We report the results of analysis of VHE data taken during 1998 March and April and 1999 February. We present the results of a search for a possible correlation between > 400 GeV gamma rays recorded by the University of Durham Mark 6 telescope and X-ray emission according to measurements made with the *RXTE*/ASM and *CGRO*/BATSE experiments. We also present the results of searches for modulation of the emission at both the orbital and spin periods.

2. Observations of VHE gamma rays

Observations were made with the University of Durham Mark 6 imaging gamma ray telescope operating at Narrabri NSW, Australia. The telescope is described elsewhere (Armstrong et al. 1999). It employs a 109-element imaging camera to discriminate gamma rays from hadrons and three

Send offprint requests to: T.J.L. McComb (t.j.l.mccomb@dur.ac.uk)

Table 1. Observing log for observations of Centaurus X-3 made with the University of Durham Mark 6 telescope at Narrabri, NSW, Australia. The numbers of ON and OFF source counts are the number of events surviving after data cleaning (see text).

Date	No. of scans ON source	ON source counts	OFF source counts
1997 March 1	4	8 627	8 776
1997 March 3	7	14 955	15 077
1997 March 4	4	8 087	8 173
1997 June 1	5	7 193	7 226
1997 June 2	6	10 690	10 565
1997 June 4	5	5 146	5 152
1997 June 5	5	8 553	8 662
1997 June 7	5	8 520	8 613
1998 March 27	6	15 844	16 083
1998 March 29	7	17 266	17 423
1998 March 30	4	10 985	11 138
1998 April 17	2	5 046	5 003
1998 April 19	4	8 456	8 398
1998 April 26	2	2 891	2 923
1998 April 27	11	16 105	16 188
1998 April 28	7	9 263	9 069
1998 April 29	3	4 681	4 782
1999 February 13	5	11 547	12 015
1999 February 15	6	11 044	11 499
1999 February 16	11	25 606	26 083
1999 February 17	12	24 797	24 942
1999 February 20	3	6 789	6 779
1999 February 21	5	8 463	8 183

$42\ \mathrm{m}^2$ flux collectors on a single mount to obtain an energy threshold of about 300 GeV. The telescope was operational from 1995 to 1999.

The results of initial observations of Cen X-3 in 1997 have been reported previously (Chadwick et al. 1998). Our complete Cen X-3 dataset comprises data from 31 hrs of observation (with an equal quantity of off-source observations) during 23 exposures in 1997 March and June (JD 2 450 508 – JD 2 450 606), 1998 March and April (JD 2 450 899 – JD 2 450 932) and 1999 February (JD 2 451 220 – JD 2 4512 30). An observing log is given in Table 1.

Data were routinely taken in 15-minute segments. Off-source control observations were taken by alternately observing regions of sky which differ by ± 15 minutes in RA from the position of Cen X-3 to ensure that on- and off-source segments have identical zenith and azimuth profiles and cosmic ray background response. The choice of alternate off-source segments which precede and follow the on-source segment allows for any small residual secular effects.

The data analysis employed follows the methods established in our previous detections of VHE emission from of Cen X-3 (Chadwick et al. 1998), PKS 2155–304 (Chadwick et al. 1999a) and the determination of limits from a range of extragalactic objects (Chadwick et al. 1999b) and pulsars (Chadwick et al. 2000). Data were accepted for analysis only if the sky was clear and stable and the gross counting rates in each on-off segment pair were consistent at the $2.5\ \sigma$ level. In our later observations, the sky clarity was assessed using an infra-red radiometer mounted paraxially with the telescope (Buckley et al. 1999).

Events were considered suitable for further analysis ("cleaned") if they were confined to within 1.1° of the centre of the camera, and that they had sufficient information for reliable data analysis. For our analysis of the Cen X-3 dataset, a slightly larger size cut than has been employed in our PKS 2155–304 analysis has been used (800 digital counts rather than 500). This reflects the noisier images caused by the bright source field close to Cen X-3 and by the consequent running of the camera at a reduced HT setting. The number of ON and OFF source events remaining after this cleaning process is shown in Table 1.

Gamma ray candidates were selected using similar criteria to those employed in our detection of VHE gamma rays from PKS 2155–304. Gamma rays are selected through the shape of their images, using the criteria shown in Table 2. The parameters are as defined in Chadwick et al. (1999a). Slight differences in the values of the parameters used reflect the different zenith angle distributions and the effects of sky brightness. The final selection was based on the value of the pointing angle *ALPHA*, where a value less than 30° was an indication of a gamma ray candidate.

Our earlier report (Chadwick et al. 1998) was based on data recorded in 1997 March and June (JD 2 450 508 – JD 2 450 606) only. Assuming a collection area of $10^9\,\mathrm{cm}^2$ and that our selection procedure retained $\sim 50\%$ of the original gamma ray events, the time averaged flux was estimated to be $(2.0 \pm 0.3) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for > 400 GeV. Ongoing simulations suggest that our current selection procedure retains $\sim 20\%$ of the gamma rays. On this basis, the flux for the 1997 March and June (JD 2 450 508 – JD 2 450 606) data would be $(5.0 \pm 0.9) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The additional data taken in 1998 and 1999 provide fewer gamma ray candidates suggesting weaker TeV emission. In total, there were 617 excess events identified as gamma rays detected in 108 360 seconds of ON-source observation. Assuming, as above, a collection area of $10^9\,\mathrm{cm}^2$ and that the current selection procedure retains $\sim 20\%$ of the original gamma ray events this yields a time averaged flux of $(2.8 \pm 1.4_{\mathrm{sys}} \pm 0.6_{\mathrm{stat}}) \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at an average gamma ray threshold of ~ 400 GeV, defined as the energy at which the triggering probability was $\sim 50\%$. The significance of the detection based on the total dataset is $4.7\ \sigma$.

3. The TeV gamma ray signal strength

Our recent work on PKS 2155–304 (Chadwick et al. 1999a) has demonstrated a method of assessing the signal strength of gamma rays recorded by Cherenkov telescopes. It is suited to measurements made at different epochs and at different zenith angles when the telescope has different sensitivities and consequently a varying background cosmic ray detection rate. We have estimated the strength of TeV gamma ray emission by expressing it as a fraction of the cosmic ray background remaining after image shape and orientation selection (Fegan 1997). In so

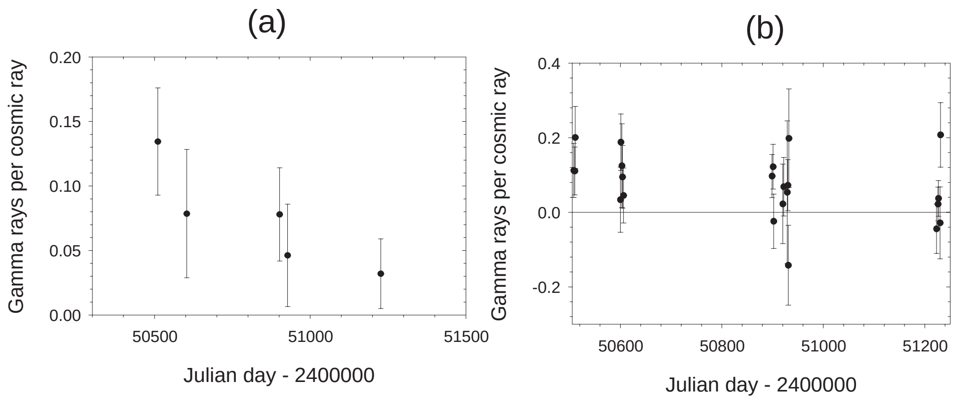

Fig. 1. a The VHE gamma ray flux from Cen X-3 averaged over observing periods. **b** The VHE gamma ray flux from Cen X-3 plotted on a day-by-day basis.

Table 2. The image parameter selections applied to the analysis of data from the Cen X-3 data.

Parameter	Ranges	Ranges	Ranges	Ranges
SIZE (d.c.)	800–1 200	1 200–1 500	1 500–2 000	2 000–10 000
DISTANCE	$0.35° - 0.85°$	$0.35° - 0.85°$	$0.35° - 0.85°$	$0.35° - 0.85°$
ECCENTRICITY	0.35–0.85	0.35–0.85	0.35–0.85	0.35–0.85
WIDTH	$< 0.20°$	$< 0.23°$	$< 0.28°$	$< 0.32°$
CONCENTRATION	< 0.50	< 1.0	< 0.40	< 1.0
$D_{\rm dist}$	$< 0.18°$	$< 0.16°$	$< 0.10°$	$< 0.07°$

doing we make allowances for variations in sensitivity, in first order, due to changes in efficiency of the telescope and variations in telescope performance with zenith angle. It is also assumed that the slopes of the gamma ray and cosmic ray spectra are similar.

In the present study, the average gamma ray signal strength from Cen X-3, expressed as a percentage of the cosmic ray background remaining after shape and orientation selection is (7.0 ± 1.5)%. The most straightforward, but not most powerful, test for constancy of emission is to repeat this process for the data recorded in each of the 5 dark periods as shown in Fig. 1a and then test for consistency between the values obtained using a χ^2 test. On the basis of this test we find no internal evidence for monthly variability of the VHE signal; the data treated this way are consistent with a constant signal strength ($\chi^2 = 4.5$, 4 df).

4. X-ray and VHE gamma ray correlations

Cen X-3 is a strong but variable X-ray emitter. For example, the average daily rates for X-rays detected with the *RXTE*/ASM during 1997 and 1998 range from 0 to 32 counts s^{-1}; the data are variable on a time scale of days. The daily average for the *RXTE*/ASM count rates are available for 22 of the 23 days when VHE gamma ray observations were made[1].

The strength of pulsed X-ray emission was also available as a daily average from the BATSE archive for 1997[2]; during the 1998 and some of the 1999 VHE observations, the X-ray flux was below the threshold for BATSE detection. The BATSE data provide a series of independent X-ray measurements, including a measurement on the single day of the TeV gamma ray observations for which there is no corresponding *RXTE*/ASM measurement.

The VHE gamma ray signal plotted on a day by day basis is shown in Fig. 1b. There is no evidence for outbursts of TeV gamma ray emission on a timescale of days and the data are consistent with a constant VHE gamma ray flux ($\chi^2 = 22.1$, 22 df).

In Fig. 2a we show the relation between the count rate of the *RXTE*/ASM data and our gamma ray signals. In Fig. 2b we show a similar plot relating the individual BATSE pulsed X-ray fluxes and our gamma ray signals. We have no formal evidence for a correlation, although it is interesting to note that the day of highest detected gamma ray flux coincides with the day of most X-ray activity in the dataset (1997 March 4).

5. Modulation

We have searched for modulation of the gamma ray signal at the orbital period of the binary system. The orbital phase of each of our observations has been calculated using the ephemeris of Kelley et al. 1983. The results are shown in Fig. 3. We conclude that there is no significant modulation of the VHE gamma ray emission at the orbital period.

We have also looked for modulation in the VHE data at the pulsar period. The total dataset has been subjected to a Rayleigh test for periodicity at a small range of periods around the pulsar period found in the contemporary BATSE data. Phase coherence between observations was not assumed. No significant periodicity was detected, leading to a 3σ upper limit of

[1] Available on the web at
http://space.mit.edu/XTE/asmlc/srcs/cenx3.html
[2] Original data obtained from the web at
http://www.batse.msfc.nasa.gov/data/pulsar

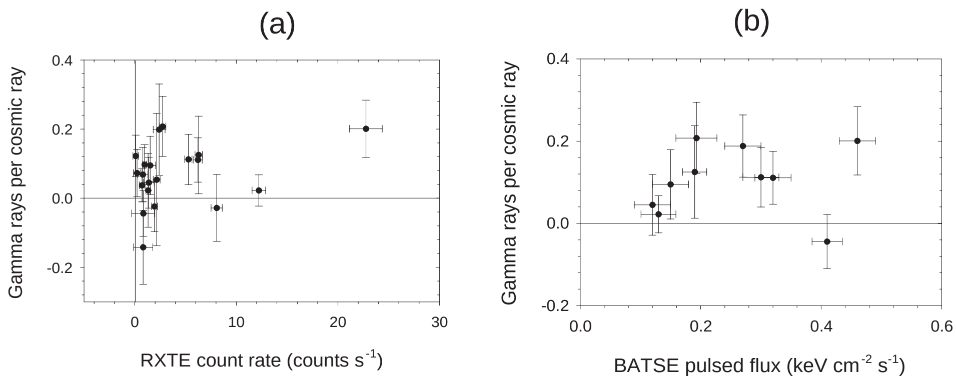

Fig. 2a and b. The relation between the daily VHE gamma ray flux from Cen X-3 and **a** the X-ray flux detected by ASM/*RXTE* and **b** the X-ray pulsed flux detected by BATSE.

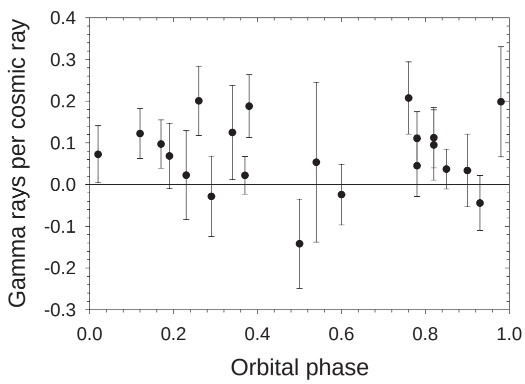

Fig. 3. The measured VHE gamma ray rate during each observation of Cen X-3 plotted as a function of orbital phase.

$2.0 \times 10^{-12}\,\mathrm{cm^{-2}\,s^{-1}}$ to the flux pulsed at the pulsar period for an energy threshold of 400 GeV.

We have also looked for modulation at the pulsar period in each individual night's observations by searching for periodicity at the contemporary BATSE pulsar period, and so looking for VHE emission originating from the same site as the X-rays. No such emission was found.

6. Discussion

In the 1980's there was a large number of reports of VHE gamma ray emission from X-ray binaries made with first-generation non-imaging telescopes (for a review see e.g. Chadwick et al. 1990). Initial observations with imaging telescopes, especially in the northern hemisphere, failed to substantiate these detections and the evidence for VHE emission from X-ray binaries has been questioned (for a recent review see Hoffman et al. 1999).

However, recent observations of a number of X-ray binaries with the EGRET detector have shown the possibilty of high energy emission from these objects. A source consistent with the position of Cyg X-3 has been seen at good significance in the EGRET data but does not exhibit the characteristic 4.8 hr orbital modulation (Michelson et al. 1992; Mori et al. 1997). There is good evidence for emission from Cen X-3 (Vestrand et al. 1997) in the EGRET data. The enigmatic binary source LS I $+61^{\circ}303$ has been suggested as an emitter at energies above 100 MeV (Kniffen et al. 1997) and above 1 GeV (Lamb & Macomb 1997). The putative X-ray binary SAX J0635+0533 has also been associated with the EGRET source 2EG J0635+0521 (Kaarat et al. 1999; Cusumano et al. 2000).

The lack of orbital modulation in our VHE data can be used to rule out a number of models of VHE emission. Moskalenko and co-workers have developed a model where the VHE gamma rays are produced close to the neutron star (Moskalenko et al. 1993; Moskalenko & Karakula 1994). A characteristic of such a model is that the VHE emission will exhibit an orbital modulation due to pair production by the gamma rays on the photon field around the companion star. When applied to Cen X-3, this model leads to a prediction of VHE emission confined to orbital phases between 0.35 and 0.65 at energies of ~ 400 GeV. Detection of VHE emission at orbital phases other than those predicted does not support this model.

Aharonian & Atoyan (1991, 1996) have discussed a model for VHE gamma ray production in X-ray binaries where a beam of relativistic particles interacts with a moving gas target which has been ejected by the companion star. This model was proposed to explain the episodic emission of pulsed VHE gamma rays seen in earlier observations. Although the model is optimised to produce pulsed gamma rays, the dimensions and density of the gas target are critical; non-optimal target sizes can cause the coherence to be lost. Thus the lack of a pulsed signal in these observations does not necessarily exclude models of this class. Although the model predicts natural timescales of ~ 1 h for the interaction of the particle beam with the gas cloud, the sensitivity of the present measurements is not enough to distinguish such episodes.

An interesting model for production of VHE emission in accreting X-ray binaries is that of Katz & Smith (Katz & Smith 1988; Smith et al. 1992). The model is based on proton acceleration due to turbulence in the accretion column which, in turn, produces fluctuations in the strength of the magnetic field which travels up the accretion column. This results in acceleration of protons to high energy via resonant absorption in the outer regions of the magnetosphere. As well as predicting the existence of VHE gamma rays, this model also predicts that the protons will emit synchrotron radiation up to ~ 1 GeV, that there will be detectable fluctuations in the X-ray signal on millsecond timescales due to turbulence in the accretion column and the possibility of the synchrotron radiation being detectable in the infrared. The observations of GeV emission from Cen X-3 (Vestrand et al. 1997) and kHz fluctuations in the X-ray intensity (Jernigan et al. 2000) indicate that such a model for VHE production should be re-evaluated. We also note that the epoch at which kHz fluctuations were observed (JD 2 450 507 – JD 2 450 512, Jernigan et al. 2000) overlaps with with our most significant and strongest VHE detection (JD 2 450 508 – JD 2 450 511).

7. Conclusions

We have detected VHE gamma ray emission from Cen X-3 during each dark moon period that we have observed this object. The data are consistent with a weak but persistent emission, both when the VHE data is averaged over dark moon periods and when considered observation by observation. Although the observation that yields the strongest gamma ray flux occurs on the day when the daily averaged *RXTE* X-ray flux was the highest of any day on which we observed Cen X-3, there is no evidence for a formal correlation between the VHE gamma-ray and X-ray fluxes.

We have also tested for modulation of the VHE gamma ray flux at the orbital period of the binary system and at the pulsar period. We have no evidence for modulation of the VHE gamma ray emission at either period.

The model of Katz and Smith (Katz & Smith 1988; Smith et al. 1992) for VHE gamma ray production in X-ray binaries is shown to be consistent with the VHE observations, especially in the light of its prediction of kHz fluctuations in X-ray intensity which have been observed during one of the epochs of VHE emission (Jernigan et al. 2000). As well as gamma ray emission at EGRET energies, the Katz and Smith model predicts an infrared excess from Cen X-3. It is suggested that IR observations of Cen X-3 should be made, especially as part of future multiwavelength studies.

Acknowledgements. We are grateful to the UK Particle Physics and Astronomy Research Council for support of the project. The Mark 6 telescope was designed and constructed with the assistance of the staff of the Physics Department, University of Durham. The efforts of Mr. P. Cottle, Mrs. E.S. Hilton and Mr. K. Tindale are acknowledged with gratitude. This paper uses quick look results provided by the ASM/*RXTE* and BATSE teams. We would like to thank the referee, Professor Christo Raubenheimer, for helpful comments on the original manuscript.

References

Aharonian F.A., Atoyan A.M., 1991, ApJ 381, 220
Aharonian F.A., Atoyan A.M., 1996, Space Sci. Rev. 75, 357
Armstrong P., Chadwick P.M., Cottle P.J., et al., 1999, Experimental Astron. 9, 51
Bowden C.C.G., Bradbury S.M., Chadwick P.M., et al., 1993, Proc. 23rd. Int. Cosmic Ray Conf. (Calgary) 1, 298
Brazier K.T.S., Carramiñana A., Chadwick P.M., et al., 1990, Proc. 21st. Int. Cosmic Ray Conf. (Adelaide) 2, 296
Buckley D.J., Dorrington M.C., Edwards P.J., et al., 1999, Experimental Astron. 9, 237
Burderi L., Di Salvo T., Robba N.R., et al., 2000, ApJ 530, 429
Carramiñana A., Chadwick P.M., Dipper N.A., et al., 1989, In: Ögelman H., van den Heuvel E.P.J. (eds.) Timing Neutron Stars. Kluwer Academic Press, Dordrecht, p. 369
Chadwick P.M., McComb T.J.L., Turver K.E., 1990, J. Phys. G. Nucl. Part. Phys. 16, 1773
Chadwick P.M., Dickinson M.R., Dipper N.A., et al., 1998, ApJ 503, 391
Chadwick P.M., Lyons K., McComb T.J.L., et al., 1999a, ApJ 513, 161
Chadwick P.M., Lyons K., McComb T.J.L., et al., 1999b, ApJ 521, 547
Chadwick P.M., Lyons K., McComb T.J.L., et al., 2000, ApJ 537, 414
Cusumano G., Maccarone M.C., Nicastro L., 2000, ApJ 528, L25
Fegan D.J., 1997, J. Phys. G. Nucl. Part. Phys. 23, 1013
Hoffman C.M., Sinnis C., Fleury P., et al., 1999, Rev. Mod. Phys. 71, 897
Hutchings J.B., Cowley A.P., Crampton D., et al., 1979, ApJ 229, 1079
Jernigan J.G., Klein R.I., Arons J., 2000, ApJ 530, 875
Kaarat P., Piraino S., Halpern J., et al., 1999, ApJ 523, 197
Katz J.I., Smith I.A., 1988, ApJ 326, 733
Kelley R.L., Rappaport S., Clark G.W., et al., 1983, ApJ 268, 790
Kniffen D.A., Alberts W.C.K., Bertsch D.L., et al., 1997, ApJ 486, 126
Krzemiński W., 1974, ApJ 192, L135
Lamb R.C., Macomb D.J., 1997, ApJ 488, 872
Michelson P.F., Bertsch D.L., Chiang J., et al., 1992, ApJ 401, 724
Mori M., Bertsch D.L., Dingus B.L., et al., 1997, ApJ 476, 842
Moskalenko I.V., Karakula S., Tkaczyk W., 1993, MNRAS 260, 681
Moskalenko I.V., Karakula S., 1994, ApJS 92, 567
Nagase F., Corbet R.H.D., Day C.S.R., et al., 1992, ApJ 236, 904
North A.R., Brink C., Cheng K.S., et al., 1990, Proc. 21st Int. Cosmic Ray Conf. (Adelaide) 2, 275
North A.R., Raubenheimer B.C., Brink C.. et al., 1991, Proc. 22nd Int. Cosmic Ray Conf. (Dublin) 1, 340
Priedhorsky W.C., Terrell J., 1983, ApJ 273, 709
Raubenheimer B.C., Smit H.J., 1997, Astropart. Phys. 7, 63
Santangelo A., Del Sordo S., Segreto A., et al., 1998, A&A 340, L55
Smith I.A., Katz J.I., Diamond P.H., 1992, ApJ 388, 148
Tsunemi H., Kitamoto S., Tamura K., 1996 ApJ 456, 316
Vestrand W.T., Sreekumar P., Mori M., 1997, ApJ 483, L49