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# Search for TeV gamma rays from the X-ray pulsar 1E2259+586

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**Abstract.** Evidence for TeV gamma-ray emission from 1E2259+586 has recently been reported by the Durham Group (Brazier et al. 1990). If correct, this report would be of great importance to the field of ground-based gamma-ray astronomy, as the evidence suggests that the source is a steady gamma-ray emitter, with a flux an order of magnitude higher than that of the Crab Nebula (Weekes et al. 1989). The Whipple Collaboration observed 1E2259+586 for a total of 80 h between November 1985 and November 1988 using the atmospheric Cherenkov imaging technique. These observations, including some taken over the same time span as the Durham observations, were analysed for evidence of periodic emission at the fundamental and second harmonic of the X-ray period. We find no evidence for gamma-ray emission from this source, and report an upper limit based on the imaging technique which is a factor of eight lower than the flux level reported by the Durham Group.

**Key words:** gamma rays – periodic emission

## 1. Introduction

The X-ray pulsar 1E2259+586 is situated at the centre of G109.1-1.0, a type-I supernova remnant (Gregory & Fahlmann 1980). The central compact object has been observed in IR, optical, and X-rays, while the nebula has been seen as a non-thermal radio source, and has also been detected in X-rays. A jet-like structure links the compact object with the nebula. The distance to the system is estimated to lie between 3.2 and 5 kpc (see Fahlman & Gregory 1983; Morini et al. 1988; Hanson et al. 1988 for further details).

A temporal analysis of the X-rays from the compact object shows it to be pulsating with a period of approximately 7 s. The light curve exhibits a double-peaked structure, with power in both the fundamental and second harmonic. A history of the period observations is summarized in Fig. 1 – the observed $P/\dot{P}$ is of order $4\ 10^5$ yr. A search by Fahlman & Gregory (1983) for modulation due to an orbital period indicated a possible period of 2300 s, but subsequent observations have failed to confirm this (Koyama et al. 1987; Morini et al. 1988; Hanson et al. 1988). However, the length of the X-ray pulsation and the observed X-ray luminosity of $2\ 10^{35}$ erg s$^{-1}$ suggest that 1E2259+586 is powered by accretion and hence may be part of a binary system. The system is therefore of particular interest, being the only binary apart from SS 433 which shows a convincing link with a supernova remnant. The optical companion is faint ($B = 22.0$) suggesting a compact, low-mass system (Fahlman et al. 1982). In the IR region, there is weak evidence for a 0.35% downward shift in frequency, due perhaps to beating between the spin and orbital periods (Middleditch et al. 1983).

In the very high energy region, searches have been made for emission in TeV and PeV gamma rays and in underground muon data. Weak evidence was found in data obtained by the Soudan I nucleon decay experiment for a possible muon flux from the direction of 1E2259, and a modulation was observed at a period below the expected X-ray period (Ruddick 1987). Upper limits have been reported for the emission of TeV and PeV gamma-rays by several groups (Cawley et al. 1987; Bloomer et al. 1987; Weeks 1988; Cawley et al. 1989). The Durham group, however, have recently reported evidence of TeV gamma-ray emission from this source (Brazier et al. 1989a, Brazier et al. 1990). Using an atmospheric Cherenkov telescope based at La Palma in the Canary Islands, they observed 1E2259+586 for a total of 13 h on six nights between 1988 October 4–11. After application of a discrimination technique which rejected 37% of the registered events, the remaining event times were barycentred and tested for periodicity around the X-ray period. Evidence for periodicity at a chance level of $2\ 10^{-5}$ was noted close to the second harmonic of the X-ray period, increasing to a final chance level of $5.3\ 10^{-5}$ after degrees of freedom were considered. The strength of the signal was found to be 2.1% of the cosmic ray background, corresponding to a time averaged flux of $(2.0 \pm 0.8)\ 10^{-10}$ cm$^{-2}$ s$^{-1}$ for gamma-ray energies in excess of 400 GeV. This signal was obtained after the 13 h of data spanning 8 days were linked in phase. We report here on an analysis of 80 h of data on this source spanning three years, including 13 h of data taken over the same observational interval as that of the Durham group. No evidence for gamma-ray emission is found, and a flux upper limit is derived which is more than a factor of 8 below the flux level reported by Brazier et al. (1990).

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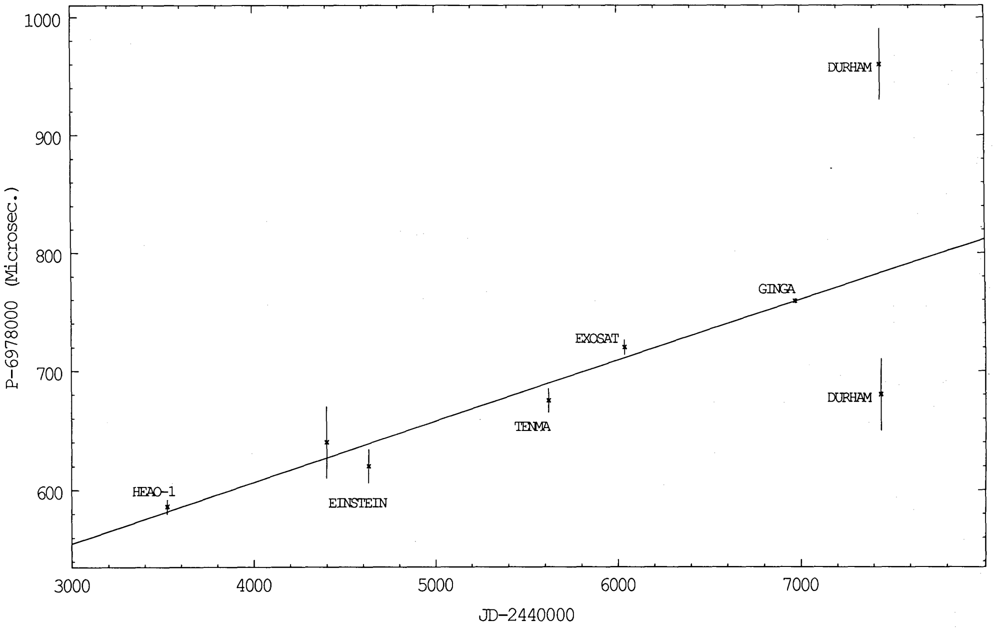

**Fig. 1.** The pulse period history of 1E 2259+586. All the X-ray points are adequately fitted by a linear spindown with $\dot{p} \simeq 5.9 \times 10^{-13}$ s s$^{-1}$ (Davies et al. 1990). References: HEAO-1 (Davies et al. 1990), Einstein (Fahlman & Gregory 1983), Tenma (Koyama et al. 1987), EXOSAT (Hanson et al. 1988), Ginga (Koyama et al. 1989), Durham TeV points (Brazier et al. 1990)

**Table 1.** Observations of 1E 2259+586 using the Cherenkov Imaging Technique

| Date (dark run) | Camera status (pixels) | Hours on source | Number of nights |
|---|---|---|---|
| 1985 November | 37 | 5 | 2 |
| 1986 Sept.–Oct. | 37 | 3 | 1 |
| 1986 Oct.–Nov. | 37 | 1 | 1 |
| 1986 Nov.–Dec. | 37 | 25 | 10 |
| 1986/87 Dec.–Jan. | 37 | 2 | 2 |
| 1987 Sept.–Oct. | 37 | 4 | 1 |
| 1987 Oct.–Nov. | 37 | 10 | 4 |
| 1988 September | 109 | 11 | 4 |
| 1988 October | 109 | 17 | 7 |
| 1988 November | 109 | 2 | 2 |
| Total | | 80 | 34 |

## 2. Observations of 1E 2259+586 using Cherenkov imaging

The Cherenkov Imaging detector at the focus of the 10 m reflector at the Whipple Observatory has been used to observe 1E 2259+586 for a total of 80 h between November 1985 and November 1988. The database is summarized in Table 1. For the 1985 to 1987 observations, the detector consisted of 37 5 cm diameter photomultiplier tubes; for the 1988 observations, the detector was upgraded to 109 PTM's, the inner 91 of diameter 2.9 cm, with a surrounding ring of 18 5 cm tubes. The majority of the data was taken as continuous tracking scans with no OFF region data, thus precluding analysis for unpulsed emission. There was a total of 61 such scans, ranging in duration from 28 to 180 min, taken on 34 nights in the three year period.

In the case of the data taken contemporaneously with the Durham group's observations, there was a total of 13.3 h of observations taken between 1988 October 5–9, consisting of 12 scans ranging in duration from 28 to 120 min. The observing conditions during this period were mostly excellent, with some non-optimal skies which were nevertheless suitable for continuous tracking for the purpose of periodicity searches. A total of 130,554 events were registered in 13.3 h, giving an average rate of 164 events/min. Most of the data was taken in the elevation range 55° to 65°. This rate is lower than the event rate of about 280/min pertinent to the observations of the Crab Nebula at similar elevations (Vacanti et al. 1990). The latter observations, from November 1988 to March 1989, were taken using the full complement of mirrors on the 10 m reflector whereas some of the mirrors had been removed for realuminising during the 1E 2259+586 observations; this accounts for the differences in event rates, and implies a somewhat higher energy threshold for the 1E 2259+586 observations.

## 3. Data analysis and results

All of the event times were initially reduced to the solar system barycentre, and each Cherenkov image was flat-fielded, filtered to reduce effects of night sky light fluctuations, and then reduced to a set of parameters which concisely describe the features pertinent to signal discirimination (for further details of the procedures used in the imaging analysis, see Weekes et al. 1989; Cawley et al. 1990). In the initial periodicity search, each of the individual 61 scans was analysed at the fundamental and second harmonic using the Rayleigh test. Period ranges of 6.9765 to 6.98056 and 3.4888 to 3.48983 s were chosen, corresponding to a single independent period for a scan of 3 h duration. These ranges encompass the observed X-ray periods for the years in question. Each scan was analysed in two ways: i) all events (no image selection), and ii) images selected using the single "azwidth" parameter which combines discrimination based on image orientation and image size – this single parameter has been found to be most effective in isolating the gamma-ray signal from the Crab Nebula (Weekes et al. 1989). The total number of trials in this analysis was 732 (61 scans, 2 harmonics, 2 cuts on the data, and an additional factor of 3 to allow for oversampling within the single independent period).

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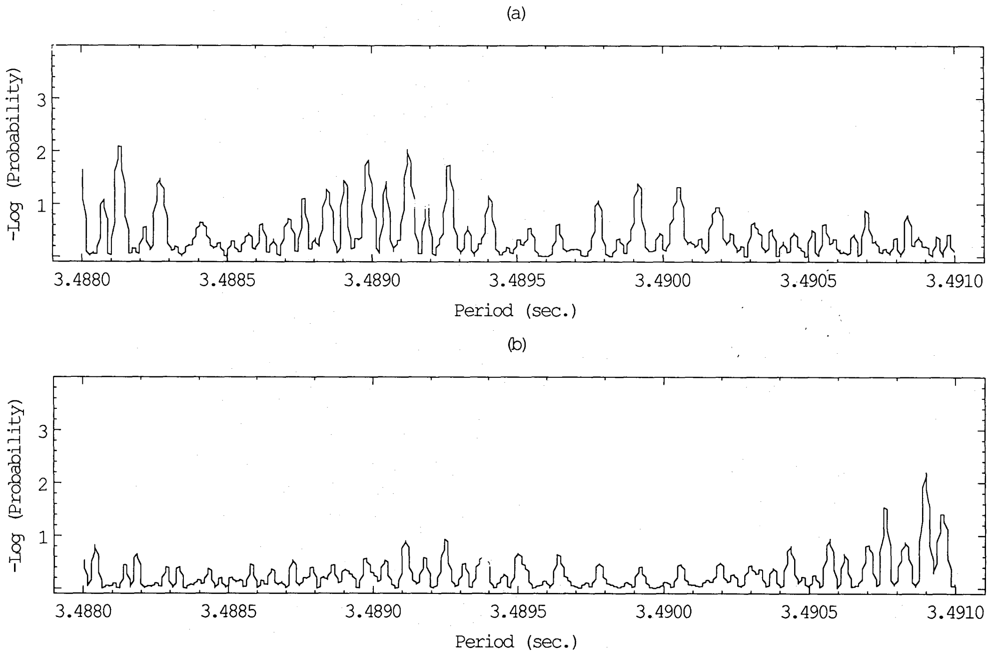

**Fig. 2a and b.** Second harmonic periodograms for the Cherenkov imaged data. The wide period range is for display purposes only; the data was tested for periodicity over the much narrower ranges given in the text; **a** all events, **b** "azwidth" selected events

The maximum observed Rayleigh power was 8.1, increasing to a final probability of chance occurrence of 20% after consideration of the trials. Lower powers were found to be distributed in a manner compatible with the absence of any signal. There is thus no evidence for sporadic TeV emission on timescales of 0.5 to 3 h in the database. To test for the possibility of weak, continuous emission, all the periodograms associated with the individual scans were combined incoherently. Again, no significant signal was evident. To allow for the possibility of the TeV period being shifted from the X-ray period (as has been observed in the case of Her X-1; see Lamb et al. 1988), the above analysis was repeated over a wider range of periods, ±0.5% about the expected X-ray period. Again, no effect was found. Finally, to test for emission lasting several nights, the data was analysed coherently in 10 dark-run groups (see Table 1). No significant evidence for TeV emission was found at either harmonic.

In the light of the recent report by Brazier et al. (1990) for strong periodic TeV emission from this source, the particular subset of our data taken contemporaneously with that of the Durham group was reanalysed using the same period ranges as in Brazier et al. (1990) to permit direct comparison between the two sets of observations. As before, two datasets were formed: the first consisted of all the trigger events linked in phase from night to night (130,554 events) and the second consisted of all events passing the azwidth cut (3496 events). Each of the two datasets were tested for periodicity using the Rayleigh test over the same period ranges as used in Brazier et al. (1990), namely 6.9786–6.9792 s and 3.4893–3.4896 s. All the resulting periodograms were consistent with chance. The second harmonic periodograms are shown in Fig. 2 (a wider range of period is used for illustrative purposes). Assuming a collection area of $3\ 10^8\ \mathrm{cm}^2$, we estimate a 95% confidence flux upper limit of $2.4\ 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for energies in excess of 600 GeV on the basis of the null result in the imaged data. This should be compared with the flux reported by Brazier et al. (1990) of $(2.0 \pm 0.8)\ 10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ ($E > 400$ GeV) for contemporaneous observations (Fig. 3).

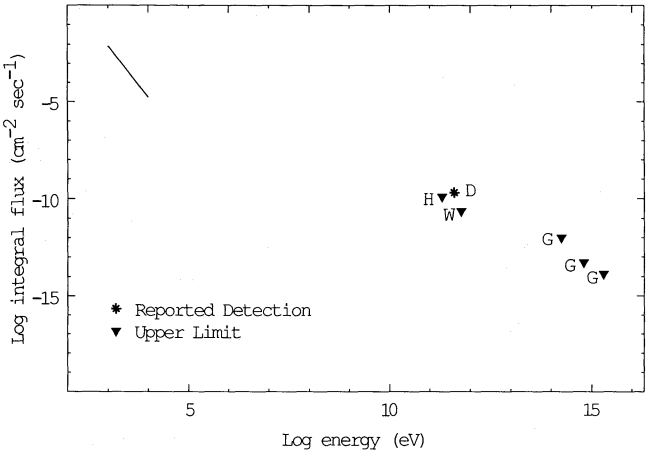

**Fig. 3.** Flux measurements and upper limits for 1 E 2259 + 586. The continuous line indicates the high energy tail of the X-ray spectrum (Hanson et al. 1988). H = Haleakala unpulsed limit (Weeks 1988), D = Durham point (Brazier et al. 1990), W = Whipple Collaboration pulsed limit (this work), G = Grex unpulsed limits (Bloomer et al. 1987)

## 4. Discussion

A difference of more than a factor of 8 between the flux level reported by Brazier et al. (1990) and the 95% confidence upper limit of the present work cannot easily be explained; such conflicts in the past have usually been ascribed to the sporadic nature of TeV gamma-ray sources, but this explanation is extremely unlikely in the present instance, given the contemporaneous nature of the observations. Furthermore, the fact that the Durham group saw evidence for TeV emission from 1 E 2259 + 586 on their only reported observations of this source would suggest that the source is a steady emitter at these energies (similar to the Crab

Nebula – Weekes et al. 1989). This makes reconciliation of the observations of the two experiments even more difficult, as we have monitored the source on many instances over a three-year period and have never seen evidence for TeV gamma-ray emission. Possible explanations for this conflict are the following:

*1) The source spectrum is extremely steep:* The lack of a full mirror complement coupled with the relatively low elevation of the source meant that the threshold of the high resolution imaging camera was somewhat higher than for the Crab Nebula observations taken during the following months. However, in order for the source flux to drop from $2\ 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 400 GeV to below $2.4\ 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 600 GeV would require an integral source spectral index in excess of 5; such a rapid decline over a narrow energy range would be most unlikely.

*2) The Durham guard-ring approach is more sensitive than the Whipple High Resolution Cherenkov Imaging Technique:* In the light of our detection of the Crab Nebula at very high levels of statistical significance using the Cherenkov Imaging technique (in excess of 20 standard deviations above the background level, Vacanti et al. 1990), there remains no doubt that this technique is a highly sensitive TeV gamma-ray detection method. It should be noted that over 97% of the background is rejected upon application of the azwidth discriminant, while both simulations and the Crab Nebula effects would indicate that at least 50% of the original gamma-ray signal is retained (Lang et al. 1990). This leads to an enhancement of the original unimaged significance by a factor

$$Q_{\text{imaging}} = 0.5/\sqrt{(0.03)} = 2.9\,,$$

(i.e. a 2 sigma effect in the raw data would become a 5.8 sigma effect after application of the imaging discriminant). In contrast, the Durham guard-ring algorithm (Brazier et al. 1989b) reduces the total number of registered events on 1E 2259+586 from 37,564 to 23,585, i.e. a background rejection of 37%. Even if it is assumed that 100% of the signal is retained in this process, the best enhancement factor that can be acchieved relative to a telescope which does not use the guard-ring method is

$$Q_{\text{guard-ring}} = 1.0/\sqrt{(0.63)} = 1.3\,,$$

(a 2 sigma effect in the raw data would become 2.6 sigma after application of the guard-ring algorithm). It would appear, therefore, that the guard-ring method is not more sensitive than the Cherenkov imaging technique.

*3) Cherenkov imaging is not a proven technique:* The experimental verification of the Cherenkov imaging technique relies on the effects observed from the Crab Nebula (Weekes et al. 1989; Vacanti et al. 1990). If these effects are not genuine, then the arguments in (2) above would not be valid. The statistical significance of the effects reported in Weekes et al. (1989) and Vacanti et al. (1990) are such as to leave no doubt that an excess of events has been detected in the direction of the Crab Nebula. There remains the question of possible systematic effects which might mimic the behaviour of a gamma-ray excess. The effect has, however, been independently verified (Akerlof et al. 1990) and we have tested for, and eliminated, any apparent sources of systematic error.

*4) The 1E 2259+586 signal consists of non-gamma-ray neutrals:* There has been considerable speculation over the past few years with regard to the TeV and PeV emission from X-ray binaries that the signals may consist of neutral particles other than gamma rays (see, for example, Morse 1986; Hillas 1987). This could account, for example, for the anomalous muon densities found in PeV signal events (Samorski & Stamm 1983; Dingus et al. 1988) and might be responsible for the lack of response of Her X-1 to the Cherenkov imaging technique (Reynolds et al. 1990). Could 1E 2259+586 be another source of these light neutral particles (bearing in mind the hint of an anomalous signal from the source recorded in underground muon data (Ruddick 1987))? The requirement that "new physics" be invoked for such an explanation must render it highly improbable, and only conceivable if all other possibilities fail – stronger evidence is required before such a hypothesis be considered seriously. Furthermore, even before application of the imaging technique, the flux reported from this source by the Durham group is such that it should have been visible in the raw (non-imaged) data of the 10 m detector (95% confidence upper limit for a raw data effect is $1.45\ 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$). Thus, an effect should have been detected without the necessity of assuming gamma-ray primaries which is inherent in the application of the azwidth discriminant. This would, however, depend to some degree on the precise nature of the neutral primary; if hadronic, the hardware trigger used in the Cherenkov imaging system would bias *against* such a signal.

*5) The Durham effect is a statistical fluctuation:* The periods which the Durham group report as the most likely periods are significantly removed from the expected X-ray value for the epoch in question (Fig. 1). While it is possible that the pulsar suffers random spin up/spin down changes as suggested by Brazier et al. (1990), the measured X-ray periods do not tend to support this, as they are all compatible with a steady spin down (Davies et al. 1990). Nevertheless, it appears surprising to find a peak probability of $2\ 10^{-5}$ so close to the X-ray period if the effect is a statistical fluctuation.

The quoted final probability is $5.3\ 10^{-5}$, after correction for the number of degrees of freedom used by oversampling (1.77) and the number of periods within the sampling range (1.5). It is not clear to us how the latter was calculated, and the factors may be too small. It has been shown in Lewis et al. (1990) that anomalous distributions of Rayleigh power arise in the presence of large gaps in the data as is the case for both the Durham group and Whipple group 1E 2259+586 observations. This can lead to underestimation of the probability of change occurrence of large powers by more than an order of magnitude. If, in addition, other factors such as the total number of sources observed and analysed with null results are taken into consideration, the probability of chance occurrence of the Rayleigh peak might increase to an acceptable level.

We would conclude on the basis of the null result presented above from observations of 1E 2259+586 contemporaneous with the Durham group that this source is not a TeV gamma-ray emitter at the flux levels reported by Brazier et al. (1990).

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## References

Akerlof C., DiMarco J., Levy H., MacCallum C., Meyer D., Radusewicz P., Tschirhart R., Yama Z., 1990, Proc. 21st ICRC, Adelaide, OG 4.3-1

Bloomer S.D., Eames P.V.J., Lambert A., Perrett J.C., Reid R.J.O., Smith N.J.T., Watson A.A., 1987, Proc. 20th ICRC, Moscow 1, 248

Brazier K.T.S., Carraminana A., Chadwick P.M., Currell T.R., Dipper N.A., Lincoln E.W., Mannings V.G., McComb T.J.L., Orford K.J., Rayner S.M., Turver K.E., 1989a, Nucl. Phys. B (Proc. Suppl.) 14A, 196

Brazier K.T., Carraminana A., Chadwick P.M., Currell T.R., Dipper N.A., Lincoln E.W., Mannings V.G., McComb T.J.L., Orford K.J., Rayner S.M., Turver K.E., 1989b, Exp. Astron. 1, 77

Brazier K.T., Carraminana A., Chadwick P.M., Dipper N.A., Lincoln E.W., Mannings V.G., McComb T.J.L., Orford K.J., Rayner S.M., Turver K.E., 1990, Proc. 21st ICRC, Adelaide, OG 4.6-29

Cawley M.F., Lewis D.A., Fegan D.J., Gibbs K.G., Hillas A.M., Lamb R.C., Porter N.A., Reynolds P.T., Weekes T.C., 1987, Proc. 20th ICRC, Moscow 1, 240

Cawley M.F., Fegan D.J., Gibbs K.G., Hillas A.M., Kwok P.W., Lamb R.C., Lang M.J., Lewis D.A., Macomb D., Porter N.A., Reynolds P.T., Vacanti G., Weekes T.C., 1989, Proc. Workshop on "Very High Energy Gammy-ray Astronomy", Crimea, p. 165 (unpublished)

Cawley M.F., Fegan D.J., Harris K., Hillas A.M., Kwok P.W., Lamb R.C., Lang M.J., Lewis D.A., Macomb D., Reynolds P.T., Schmid D.J., Vacanti G., Weekes T.C., 1990, Exp. Astron. 1, 173

Davies S.R., Wood K.S., Coe M.J., 1990, MNRAS 245, 268

Dingus B.L., Alexandreas D.E., Allen R.C., Burman R.L., Butterfield K.B., Cady R., Chang C.Y., Ellsworth R.W., Goodman J.A., Gupta S.K., Haines T.J., Krakauer D.A., Lloyd-Evans J., Nagle D.E., Potter M., Sandberg V.D., Talaga R.L., Wilkinson C.A., Yodh G.B., 1988, Phys. Rev. Lett. 61, 1906

Fahlman G.G., Hickson P., Richer H.B., Gregory P.C., Middleditch J., 1982, ApJ 261, L1

Fahlman G.G., Gregory P.C., 1983, IAU Symp. 101, 445

Gregory P.C., Fahlman G.G., 1980, Nat 287, 805

Hanson C.G., Dennerl K., Coe M.J., Davies S.R., 1988, A & A 195, 114

Hillas A.M., 1987, Proc. 20th ICRC, Moscow 2, 362

Koyama K., Hoshi R., Nagase F., 1987, PASJ 39, 801

Koyama K., Nagase F., Ogawara Y., Shinoda K., Kawai N., Jones M.H., Williams O.R., Watson M.G., Makishima K., Ohashi T., 1989, PASJ 41, 461

Lamb R.C., Cawley M.F., Fegan D.J., Gibbs K.G., Gorham P.W., Hillas A.M., Lewis D.A., Porter N.A., Reynolds P.T., Weekes T.C., 1988, ApJ 328, L13

Lang M.J., Cawley M.F., Fegan D.J., Hillas A.M., Kwok P.W., Lamb R.C., Lewis D.A., Macomb D., Reynolds P.T., Vavanti G., Weekes T.C., 1989, Nucl. Phys. B (Proc. Suppl.) 14A, 165

Lewis D.A., Lamb R.C., Biller S.D., 1990, ApJ (in press)

Middleditch J., Pennypacker C.R., Burns M.S., 1983, ApJ 274, 313

Morini M., Robba N.R., Smith A., van der Klis M., 1988, ApJ 333, 777

Morse R., 1986, Proc. Workshop on "Very High Energy Gamma-ray Astronomy", Durham, NATO ASI Series C, 199, 197, Reidel, Dordrecht

Reynolds P.T., Cawley M.F., Fegan D.J., Hillas A.M., Kwok P.W., Lamb R.C., Lewis D.A., Macomb D., Vacanti G., Weekes T.C., 1990, Proc. 21st ICRC, Adelaide, OG4.2-2

Ruddick K., 1986, Proc. Workshop on "Very High Energy Gamma-ray Astronomy", Durham, NATO ASI Series C, 199, 185, Reidel, Dordrecht

Samorski M., Stamm W., 1983, ApJ 268, L17

Vacanti G., Cawley M.F., Fegan D.J., Hillas A.M., Kwok P.W., Lamb R.C., Lang M.J., Lewis D.A., Macomb D., Reynolds P.T., Weekes T.C., 1990, ApJ (submitted)

Weekes T.C., Cawley M.F., Fegan D.J., Gibbs K.G., Hillas A.M., Kwok P.W., Lamb R.C., Lewis D.A., Macomb, D., Porter N.A., Reynolds P.T., Vacanti G., 1989, ApJ 342, 379

Weeks D.D., 1988, Ph.D. Dissertation, University of Hawaii (unpublished)