THE ASTROPHYSICAL JOURNAL, 372:L75–L78, 1991 May 10

CODED-APERTURE IMAGING OF THE GALACTIC CENTER REGION AT GAMMA-RAY ENERGIES

WALTER R. COOK, JOHN M. GRUNSFELD, WILLIAM A. HEINDL, DAVID M. PALMER, THOMAS A. PRINCE,
STEPHEN M. SCHINDLER, AND EDWARD C. STONE
Division of Physics, Mathematics, and Astronomy, California Institute of Technology, M.S. 220-47, Pasadena, CA 91125

Received 1990 December 26; accepted 1991 February 26

ABSTRACT

The first coded-aperture images of the Galactic center region at energies above 30 keV have revealed two strong γ-ray sources. One source has been identified with the X-ray source 1E 1740.7−2942, located $0\overset{\circ}{.}8$ away from the nucleus. If this source is at the distance of the Galactic center, it is one of the most luminous objects in the galaxy at energies from 35 to 200 keV. The second source is consistent in location with the X-ray source GX 354+0 (MXB 1728−34). In addition, γ-ray flux from the location of GX 1+4 was marginally detected at a level consistent with other post-1980 measurements. No significant hard X-ray or γ-ray flux was detected from the direction of the Galactic nucleus (Sgr A*), or from the direction of the recently discovered γ-ray source GRS 1758−258.

Subject headings: galaxies: The Galaxy — gamma rays: general — X-rays: sources

1. INTRODUCTION

Observations from Spacelab 2 (Skinner et al. 1987) and Spartan 1 (Kawai et al. 1988) between 1 and 30 keV, together with earlier results from the *Einstein* observatory between 0.9 and 4 keV (Watson et al. 1981; Hertz & Grindlay 1984), identified several point sources within approximately 1° of the Galactic nucleus, including a point source at the nucleus itself. At higher energies, observations by nonimaging instruments with wide fields of view (FWHM > 15°) detected 0.511 MeV positron annihilation line radiation and hard continuum emission extending above 1 MeV from the general direction of the Galactic center (e.g., Riegler et al. 1981; Leventhal et al. 1982; Riegler et al. 1985; Leventhal et al. 1989). Both line and continuum components were found to vary in intensity on time scales as short as 6 months. The compact source size required by the time variability, and the unusual γ-ray spectrum, have stimulated considerable speculation on the nature of the source of emission.

In this paper, we report γ-ray flux measurements based on the first coded-aperture imaging observations of the Galactic center region at γ-ray energies (30 keV–7 MeV). The initial report of these observations (Cook et al. 1989) discussed the detection of a strong γ-ray source that was tentatively identified as the X-ray source 1E 1740.7−2942 (Hertz & Grindlay 1984), consistent with the Spacelab 2 observation of this source as dominant in the region at 19–30 keV (Skinner et al. 1987). Further analysis of our data confirmed 1E 1740.7−2942 as the source of the primary γ-ray emission, and in addition revealed a second source, consistent in location with the X-ray burst source GX 354+0 (Cook et al. 1990a). Here we present improved γ-ray flux measurements for 1E 1740.7−2942 and GX 354+0.

2. OBSERVATIONS

The observations were performed with the Caltech Gamma-Ray Imaging Payload (GRIP), a balloon borne coded-aperture telescope sensitive to photons in the energy range from 30 keV to 10 MeV (Althouse et al. 1985). The instrument employs a rotating hexagonal-celled uniformly redundant array (HURA) and a position-sensitive NaI(Tl) scintillation detector to image a 14° diameter field of view with $1\overset{\circ}{.}1$ angular resolution.

The Galactic center region was observed for two 4 hr periods during the interval 1988 April 12.62 to 13.00 UT, as part of a 30 hr balloon flight of the instrument from Alice Springs, NT, Australia. The data were processed in seven segments of somewhat more than one hour each. For each segment a single strong point source of γ-ray emission was detected at energies between 35 and 200 keV. Data was available from an on-board CCD star camera to determine the absolute position of the source emission in four of the seven observation periods, leading to the identification of the strong γ-ray source as 1E 1740.7−2942 (Cook et al. 1990a). The remaining three observation periods occurred during daylight when no stars were visible in the CCD camera.

We used the strong source, identified as 1E 1740.7−2942, as a pointing reference to co-align images from all the separate 1 hr segments. This procedure reduced possible blurring effects resulting from pointing uncertainties and allowed images from all the segments, including the last three which lacked star camera data, to be combined in a search for weaker sources. A second source was detected in the energy range from 23 to 122 keV, as shown in Figure 1 (where the primary peak has been aligned with 1E 1740.7−2942). The presence of the second peak, consistent in location with the known X-ray source, GX 354+0, further supported the identification of the primary peak with 1E 1740.7−2942.

Flux measurements and upper limits for 1E 1740.7−2942 and GX 354+0, are presented in Table 1 and Figure 2. The flux values were computed as weighted averages of values obtained in each of the seven 1 hr segments, with weights chosen to minimize the statistical error. The use of detailed instrument calibrations, including laboratory measurements of photon attenuation in passive instrument material, and the angular response of the lead collimator, has improved the accuracy of the present measurements, compared with those presented previously (Cook et al. 1988, 1990a). Flux measurements for the Crab Nebula and Pulsar, also made during the 1988 April flight, agree with previous measurements (Jung 1989, and references therein) within approximately 10% at

1991ApJ...372L..75C

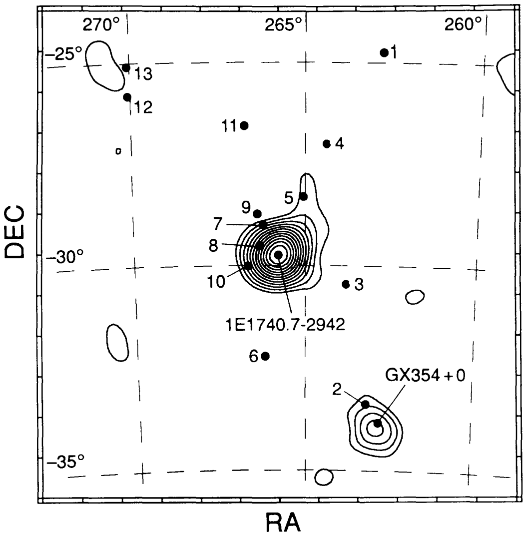

FIG. 1.— Image of the Galactic center region from 23 to 122 keV. Right ascension (*vertical lines*) and declination (*horizontal lines*) are indicated for epoch 1988.3. The contours indicate the number of excess counts in a given direction, calibrated in units of the statistical significance of the excess, with contours beginning at the 2 σ level and spaced by 1 σ. Sources 1E 1740.7−2942 and GX 354+0 are labeled by name, while other known hard X-ray sources (Bradt & McClintock 1983; Levine et al. 1984; Skinner et al. 1987) are numbered as follows: (1) GX 1+4, (2) MXB 1730−335 ("Rapid Burster"), (3) SLX 1732−304, (4) SLX 1735−269, (5) SLX 1737−282, (6) A1743−322, (7) Sgr A* (8) A 1742−294, (9) 1E 1743.1−2843, (10) SLX 1744−299, (11) GX 3+1, (12) GRS 1758−258, and (13) GX 5−1.

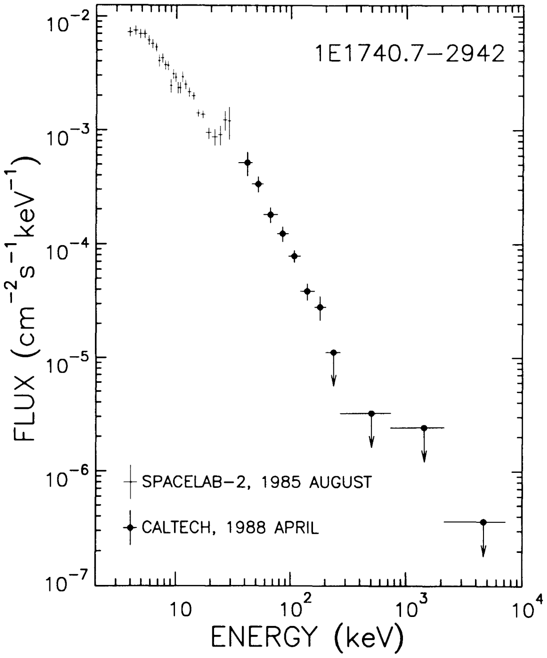

FIG. 2.—Gamma-ray differential energy spectrum measurements for the source 1E 1740.7−2942. Error bars are ±1 σ, while upper limits are at the 95% confidence level.

energies from 35 to 200 keV (Cook et al. 1990b). Details on the processing of coded-aperture images to obtain source flux measurements are given in Cook et al. (1984), Finger (1987), and Palmer et al. (1991).

Table 1 also includes results for three other sources: the Galactic nucleus radio source Sgr A*, the X-ray binary pulsar GX 1 + 4, and the recently discovered γ-ray source GRS 1758−258.

3. DISCUSSION

1E 1740.7−2942.—The identification of the strong, central γ-ray source (Fig. 1) as 1E 1740.7−2942 (Cook et al. 1990a) is consistent with the earlier imaging results from Spacelab 2 at energies below 30 keV (Skinner et al. 1987). At energies above 30 keV, the recent imaging results from SIGMA confirm our identification of 1E 1740.7−2942 as the primary hard X-ray source (Mandrou 1990). This source has not yet been identified at other than X-ray and γ-ray wavelengths.

Our spectral results for 1E 1740.7−2942, and the earlier results from Spacelab 2 (Skinner et al. 1989) are shown together in Figure 2. The hard spectrum, which distinguished 1E 1740.7−2942 from other nearby sources viewed by Spacelab 2, is seen to continue to approximately 200 keV. In the energy range from 35 to 200 keV the spectrum is well fit by a power law, $dJ/dE = K(E/100\ \text{keV})^{-\alpha}$, with spectral index

TABLE 1

GALACTIC CENTER REGION SOURCE FLUX VALUES[a]

Energy Interval	Differential Flux 10^{-5} (cm^2 s keV)$^{-1}$				Integral Flux 10^{-4} (cm^2 s)$^{-1}$	
	35–58 keV	58–122 keV	122–270 keV	270–490 keV	511 keV[b]	545–2150 keV
1E 1740.7−2942	40.6 ± 5.5	12.2 ± 1.0	1.96±0.35	<0.47	<6.8	<46.1
($\alpha = 2.05$)	(47)	(84)	(178)	(378)		
GX 354+0	38.6 ± 10.8	6.12 ± 2.03	<1.94	<0.92	<7.1	<18.0
($\alpha = 3.37$)	(46)	(79)	(199)	(378)		
GX 1+4	17.9 ± 7.5	<4.1	<0.82	<0.69	<3.7	<27.0
($\alpha = 1.9$)	(48)	(93)	(199)	(378)		
Sgr A*[c]	...	...	...	<0.65	<11.7	<52.1
				(378)		
GRS 1758−258	<19.9	<3.1	<1.1	<0.89	<7.8	<22.8
	(50)	(93)	(199)	(378)		

[a] Differential flux values correspond to a power law ($dJ/dE = KE^{-\alpha}$) evaluated at the mean energy (keV), listed in parenthesis below the corresponding flux value. The exponent, α, is given below the source name. Upper limits are quoted at 95% confidence, and assume a flat power law ($\alpha = 0$).

[b] The flux upper limits for a narrow line at 511 keV were derived by dividing the integral flux limits for a 55 keV wide energy interval by the fraction (0.87) of 511 keV photons which would be detected in that interval.

[c] Fluxes and upper limits are not given for the three lowest energy ranges. This is due to contamination from the nearby bright source 1E 1740.7−2942.

1991ApJ...372L..75C

$\alpha = 2.05 \pm 0.15$, and flux normalization, $K = 8.5 \pm 0.5 \times 10^{-5}$ cm^{-2} s^{-1} keV^{-1}.

Our results for 1E 1740.7−2942 may also be compared to earlier nonimaging measurements. Our measured spectrum falls near the lower envelope of previous flux measurements for the Galactic center region obtained at energies from about 50 keV to 1 MeV with nonimaging, wide aperture (> 10° FWHM) instruments (Matteson 1982). The higher fluxes obtained with these instruments at energies below 100 keV are probably due to the inclusion of other (possibly time-variable) hard X-ray sources such as GX 354+0 (see below) located within 10° of the Galactic center. Several instruments (Dennis et al. 1980; Matteson 1982; Levine et al. 1984; Knight et al. 1985) with relatively narrow apertures (1°.5 to 5° FWHM) have observed a source (or sources) near the Galactic center with flux at 100 keV ranging from 0.5×10^{-4} to 2.0×10^{-4} cm^{-2} s^{-1} keV^{-1}, comparable to that shown in Figure 2. Our observations strongly support the suggestion by Skinner et al. (1987) that 1E 1740.7−2942 was the source of the high energy flux seen in these earlier observations.

One possibility is that 1E 1740.7−2942 is a system similar to the black hole candidate Cyg X-1 with several states of emission, one of which produces the spectrum shown in Figure 2, and another which yields hard MeV continuum and 0.511 MeV emission. Indeed, our measured spectrum for 1E 1740.7−2942 is similar in absolute intensity and spectral shape to the γ_3 state of Cyg X-1, as measured by the *HEAO A-3* experiment in 1979 (Ling et al. 1987). Our measurements for 1E 1740.7−2942 yield a 35–200 keV luminosity of 2.1×10^{37} ergs s^{-1} (at an assumed distance of 8.5 kpc), comparable to the 50–400 keV luminosity measured for Cyg X-1 in its γ_3 state of 2.3×10^{37} ergs s^{-1} (Ling et al. 1987). Further, the spectrum of Cyg X-1 in its γ_1 state has similarities to the Galactic center spectrum measured in 1979, showing a hard excess of emission above 0.511 MeV with comparable luminosity (Lingenfelter & Ramaty 1989). Recently, a time variable hard shoulder of emission from 1E 1740.7−2942, extending from 250–600 keV, has been reported by Mandrou et al. (1990).

GX 354+0.—The X-ray burster GX 354+0 is a source of both persistent and transient X-ray emissions (e.g., Basinska et al. 1984; Hoffman et al. 1976; Hoffman et al. 1977). The X-ray intensity of the persistent source is known to vary by over a factor of ~5 (Basinska et al. 1984; Forman et al. 1978). The *Einstein* observatory measured the most intense and hot nonburst spectrum to date, and found it to be consistent with a thermal bremsstrahlung model having a temperature of $kT = 17.7$ keV (Grindlay & Hertz 1981).

Our flux measurements for GX 354+0, averaged over the entire 8 hr observation, are presented in Table 1. Comparison between our data and an extrapolation of the 17.7 keV thermal bremsstrahlung spectrum, measured by the *Einstein* observatory, yields approximate agreement, suggesting that the source may have been near its maximum nonburst brightness during our observation. From our data, the best-fit temperature, with estimated 1 σ errors, is $kT = 31\ (+23, -10)$ keV.

GX 1+4.—Observations of the X-ray binary pulsar GX 1+4, in the decade following its discovery by Lewin, Ricker, & McClintock (1971), showed the source to be one of the brightest hard X-ray sources in the Galactic center region, and to have an unusually large monotonic spin-up rate of approximately 2% yr^{-1} (Elsner et al. 1985). In contrast, during the 1980's the source was observed to be in a "low" state of emission (Makishima et al. 1988; Manchanda 1988; Sakao et al. 1990) accompanied by a halt in the rapid spin up of the pulsar. Recent observations show the pulsar spinning down (Makishima et al. 1988; Gilfanov et al. 1989; Sunyaev 1990). McClintock & Leventhal (1989) have proposed GX 1+4 as a candidate for the compact source of Galactic center 0.511 MeV emission, since this emission may have decreased in approximate correlation with the shift in observational properties of GX 1+4.

While emission from GX 1+4 is not apparent in the 23–122 keV image of Figure 1, a greater than 2 σ flux measurement was obtained in the 35–58 keV interval as listed in Table 1. This flux corresponds to 67 ± 28 mCrab at 50 keV and is in agreement with the recent measurements of Mony et al. (1989) and Sharma et al. (1990).

GRS 1758−258.—This source was recently discovered by the ART-P and SIGMA coded-aperture instruments aboard the *GRANAT* space observatory (Mandrou 1990). Our 95% confidence upper limit for the flux in the energy interval from 35 to 58 keV corresponds to 78 mCrab, and is consistent with the ART-P result of 90 ± 20 mCrab for 20 to 40 keV.

0.511 MeV *Line and* MeV *Continuum Upper Limits.*—Our 1988 April imaging observations of the Galactic center have yielded no positive detection of either 0.511 MeV line emission, or continuum emission at higher energies. Table 1 lists 95% confidence flux upper limits for the 0.511 MeV line, and for a broad continuum band from 0.55 to 2.1 MeV, as obtained for 1E 1740.7−2942, Sgr A*, GX 1+4, GX 354+0, and GRS 1758−258.

Sgr A*, the compact Galactic nucleus radio source, and more recently 1E 1740.7−2942 and GX 1+4, have been suggested as candidates for the source of the variable Galactic center positron annihilation line and hard MeV continuum emission (Lingenfelter & Ramaty 1982; Skinner et al. 1987; McClintock & Leventhal 1989). This emission was seen to turn off or decrease between the *HEAO 3* observations of 1979 Fall and 1980 Spring (Riegler et al. 1985). The flux decrease was most dramatic at energies near 1 MeV, where the continuum level dropped by a factor of 20 or more. The 0.511 MeV radiation has recently been reported to have turned on again in 1988 (Leventhal et al. 1989; Gehrels et al. 1990), then decreased by 1989 May (Matteson et al. 1989).

Our 95% confidence flux upper limits for the 0.54–2.1 MeV interval range from 1.8×10^{-3} to 5.2×10^{-3} cm^{-2} s^{-1}, and are all well below the 1979 Fall *HEAO 3* spectrum (Riegler et al. 1985), which, when integrated over the same energy range, gives $1.0 \pm 0.2 \times 10^{-2}$ cm^{-2} s^{-1}.

Our 0.511 MeV upper limits may be compared to recent Galactic center 0.511 MeV line flux measurements made with nonimaging Ge spectrometers during 1988 May and October (Gehrels et al. 1991), and 1989 May (Matteson et al. 1989). These observations yielded values of 7.5 ± 1.7, 11.8 ± 1.6, and $6.5 \pm 1.9 \times 10^{-4}$ cm^{-2} s^{-1}, respectively. Our 0.511 MeV upper limits do not conflict with the 1988 May measurement (made only 18 days after our flight), since our limits apply for isolated points in our field of view and are relatively immune to the presence of diffuse flux. After adjustment for the diffuse 0.511 MeV flux measured by *SMM* (Share et al. 1988), the portion of the 1988 May measurement which might be attributed to a compact source is only $2.8 \pm 1.7 \times 10^{-4}$ cm^{-2} s^{-1} (Gehrels et al. 1990).

In summary, we see no evidence of 0.511 MeV line emission from 1E 1740.7−2942, Sgr A*, GX 1+4, GX 354+0, or GRS 1758−258. We also did not observe a continuum excess in the energy range 250–600 keV like that reported by SIGMA (Mandrou et al. 1990) for 1E 1740.7−2942. However, the recent SIGMA observation provides evidence that transient positron annihilation may be important in 1E 1740.7−2942, strengthening the possibility that this was indeed the source of narrow positron annihilation radiation seen in observations during the 1970's and late 1980's.

We acknowledge the important contributions to the development of the GRIP telescope made by W. Althouse, D. Burke, A. Cummings, M. Finger, C. Starr, J. Weger, and the personnel of the Central Engineering Services at Caltech. We thank the personnel of the National Scientific Balloon Facility and the NASA Wallops Flight Facility for their excellent balloon launch support. This work was supported in part by NASA grants NGR 05-002-160 and NAGW-1919.

REFERENCES

Althouse, W. E., Cook, W. R., Cummings, A. C., Finger, M. H., Prince, T. A., Schindler, S. M., Starr, C. H., & Stone, E. C. 1985, Proc. 19th Internat. Cosmic Ray Conf. (La Jolla), 3, 299

Basinska, E. M., Lewin, W. H. G., Sztajno, M., Cominsky, L. R., & Marshall, F. J. 1984, ApJ, 281, 337

Bradt, H. V., & McClintock, J. E. 1983, ARA&A, 21, 13

Cook, W. R., Finger, M., Prince, T. A., & Stone, E. C. 1984, IEEE Trans. Nucl. Sci., NS-31, No. 1, 771

Cook, W. R., Grunsfeld, J. M., Heindl, W. A., Palmer, D. M., Prince, T. A., Schindler, S. M., Starr, C. H., & Stone, E. C. 1990b, Adv. Space Res., in press

Cook, W. R., Heindl, W. A., Palmer, D. M., Prince, T. A., Schindler, S. M., Starr, C. H., & Stone, E. C. 1990a, Proc. 21st Internat. Cosmic Ray Conf. (Adelaide), 1, 216

Cook, W. R., Palmer, D. M., Prince, T. A., Schindler, S. M., Starr, C. H., & Stone, E. C. 1988, in IAU Symposium 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Reidel), p. 581

Dennis, B. R., Beall, J. H., Cutler, E. P., Crannell, C. J., Dolan, J. F., Frost, K. J., & Orwig, L. E. 1980, ApJ, 236, L49

Elsner, R. F., Weisskopf, M. C., Apparao, K. M. V., Darbro, W., Ramsay, B. D., Williams, A. C., Grindlay, J. E., & Sutherland, P. G. 1985, ApJ, 297, 288

Finger, M. 1987, Ph.D. thesis, California Institute of Technology

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., & Giacconi, R. 1978, ApJS, 38, 357

Gehrels, N., Barthelmy, S., Teegarden, B., Tueller, J. Leventhal, M., & MacCallum, C. J. 1990, Bull. Am. Phys. Soc., 35, No. 4, 1081

———. ApJ, submitted

Gilfanov, M., et al. 1989, in Proc. 23d ESLAB Symposium on Two-Topics in X-Ray Astronomy, Bologna, Italy, 71

Grindlay, J. E., & Hertz, P. 1981, ApJ, 247, L17

Hertz, P., & Grindlay, J. E. 1984, ApJ, 278, 137

Hoffman, J. A., Lewin, W. H. G., & Doty, J. 1977, MNRAS, 179, 57P

Hoffman, J. A., Lewin, W. H. G., Doty, J., Hearn, D. R., Clark, G. R. W., Jernigan, G., & Li F. K. 1976, ApJ, 210, L13

Jung, G. V. 1989, ApJ, 338, 972

Kawai, N., Fenimore, E. E., Middleditch, J., Cruddace, R. G., Fritz, G. G., Snyder, W. A., & Ulmer, M. P. 1988, ApJ, 330, 130

Knight, F. K., Johnson III, W. N., Kurfess, J. D., & Strickman, M. S. 1985, ApJ, 290, 557

Leventhal, M., MacCallum, C. J., Barthelmy, S. D., Gehrels, N., Teegarden, B. J., & Tueller, J. 1989, Nature, 339, 36

Leventhal, M., MacCallum, C. J., Huters, A. F., & Stang, P. D. 1982, ApJ, 260, L1

Levine, A. M., et al. 1984, ApJS, 54, 581

Lewin, W. H. G., Ricker, G. R., & McClintock, J. E. 1971, ApJ, 169, L17

Ling, J. C., Mahoney, W. A., Wheaton, W. A., & Jacobson, A. S. 1987, ApJ, 321, L117

Lingenfelter, R. E., & Ramaty, R. 1989, ApJ, 343, 686

———. 1982, in AIP Conf. Proc. No. 83, The Galactic Center, ed. G. R. Riegler & R. D. Blandford (New York: AIP), p. 148

Makishima, K., et al. 1988, Nature, 333, 746

Manchanda, R. K. 1988, A&SS, 150, 31

Mandrou, P. 1990, IAU Circ., No. 5032

Mandrou, P., Roques, J. P., Sunyaev, R., Churazov, E., Paul, J., & Cordier, B. 1990, IAU Circ. No. 5140

Matteson, J. L. 1982, in AIP Conf. Proc., No. 83, The Galactic Center, ed. C. R. Riegler & R. D. Blandford (New York: AIP), p. 109

Matteson, J., et al. 1989, IAU Circ., No. 4889

McClintock, J. E., & Leventhal, M. 1989, ApJ, 346, 143

Mony, B., et al. 1989, Proc. 23d ESLAB Symposium on Two-Topics in X-ray Astronomy, Bologna, Italy, 541

Palmer, D. M., Cook, W. R., Grunsfeld, J. M., Prince, T. A., Schindler, S. M., & Stone, E. C. 1991, in preparation

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., Willett, J. B., Jacobson, A. S., & Prince, T. A. 1981, ApJ, 248, L13

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., & Jacobson, A. S. 1985, ApJ, 294, L13

Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., Willett, J. B., Jacobson, A. S., & Prince, T. A. 1981, ApJ, 248, L13

Sakao, T., et al. 1990, MNRAS, 246, 11P

Skinner, G. K., et al. 1987, Nature, 330, 544

Skinner, G. K., Willmore, A. P., Foster, A. J., & Eyles, C. J. 1989, Proc. Gamma Ray Observatory Science Workshop, ed. N. Johnson, (Greenbelt: GSFC) 4-191

Share, G. H., Kinzer, R. L., Kurfess, J. D., Messina, D. C., Purcell, W. R., Chupp, E. L., Forrest, D. J., & Reppin, C. 1988, ApJ, 327, 717

Sharma, D. P., et al. 1990, Proc. 21st Internat. Cosmic Ray Conf. (Adelaide), 1, 32

Sunyaev, R., & the *GRANAT* team 1990, IAU Circ., No. 5104

Watson, M. G., Willingale, R., Grindlay, J. E., & Hertz, P. 1981, ApJ, 250, 142

Note added in proof.—A recent report by Paul et al. (in Proc. Internat Symp. on Gamma-Ray Line Astrophysics, Paris-Saclay, in press [1991]), based on SIGMA observations of the 1990 October 13 high-energy flare (250–600 keV) from 1E1740.7−2942 (Mandrou et al. 1990), strengthens the interpretation of the event as being associated with an electron-positron pair plasma.