1988ApJ...335..748S

THE ASTROPHYSICAL JOURNAL, 335:748–752, 1988 December 15

SEARCH FOR GAMMA-RAY CONTINUUM EMISSION AT MeV ENERGIES FROM THE GALACTIC CENTER REGION

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Received 1988 March 9; accepted 1988 June 6

ABSTRACT

From balloon flight data of the MPE Compton telescope, constraints on the continuum emission of the Galactic center region at MeV energies were derived. The Galactic center point source flux was found to be less than 2.8×10^{-3} cm^{-2} s^{-1} between 0.6 to 3.0 MeV, which implies that the source was in a "low-intensity state" during the time of our observation (1982 October 31) as opposed to the "high-intensity state" observed by *HEAO 3* during fall 1979. The diffuse γ-ray flux from the central region of the Galactic plane was determined to be smaller than 7.2×10^{-3} cm^{-2} s^{-1} rad^{-1} at $l = 0$ in the same energy interval (both limits are at the 2 σ confidence level). The latter limit constraints the interstellar cosmic-ray electron spectrum to be smaller than $40E_{\rm MeV} - 1.8$ cm^{-2} s^{-1} sr^{-1} MeV^{-1} between 1 and 10 MeV.

Subject headings: cosmic rays: abundances — galaxies: nuclei — galaxies: The Galaxy — gamma rays: general

I. INTRODUCTION

The study of continuum emission at MeV gamma-ray energies from the Galactic center region is of interest for two reasons. First, it may add to our understanding of the Galactic center γ-ray point source, and second, it allows the study of interstellar cosmic-ray electrons at energies of a few tens of MeV in the direction toward the Galactic center.

X-ray observations between 13 to 100 keV by the UCSD/MIT experiment on *HEAO 1* (1°.6 FWHM) have shown that about 10 X-ray point sources exist within 10° of the Galactic center (Levine *et al.* 1979). As the sum spectrum of all these sources below 50 keV can be fitted by a power-law photon spectrum with an index of about -3, the continuum emission of the source which was resolved by *HEAO 1* at the position of the Galactic center (GCX) is somewhat flatter ($\sim E^{-2.1}$ to $\sim E^{-2.6}$) and therefore is the strongest of all these sources above 50 keV. At higher energies ($\gtrsim 100$ keV) the source is highly variable in intensity on a time scale of half a year (for a review see Matteson 1982).

In the low-energy X-ray range around 1 keV the corresponding source has not yet been uniquely identified. In spite of the *HEAO 1* indication that a dominating intense source with variable emission at and above 100 keV exists at or near the center, its identification at low X-ray energies is controversial. The source 1E 1742.5−2859 detected in 1979 with 1′ resolution by *HEAO 2* (*Einstein Observatory*, 0.5 to 4.5 keV) contains Sgr A West, and is supposed to be associated with the galactic nucleus (Watson *et al.* 1981). The coded mask proportional counter telescope flown by the University of Birmingham group on Spacelab 2 in 1985 only marginally saw the *Einstein* Galactic center source (Skinner *et al.* 1987) between 2.5 and 30 keV, and the collimated proportional counter system that flew on *Spartan 1* in 1985 June did not see the source at all between 1–15 keV (Kawai *et al.* 1988). If only the high-energy range (19–30 keV) of the Spacelab 2 data is considered, the *Einstein* source is no longer visible; instead the region is dominated by 1E 1740.7−2942, an *Einstein* source about 50′ away from the Galaxy. The Spacelab 2 observations therefore suggest that the strong variable flux at and above 100 keV from the general direction of the Galactic center is not associated with activity in the nucleus itself, but with the unidentified source 1E 1740.7−2942.

Strong variable continuum γ-ray flux extending to about 2 MeV has been detected together with variable 511 keV annihilation line radiation from the general direction of the Galactic center by *HEAO 3* (Riegler *et al.* 1981, 1985), and by the balloon-borne germanium spectrometer of the Bell/Sandia group (Leventhal, MacCallum, and Stang 1978). Though the direction of this emission is known only to $\sim 10°$, it is, of course, tempting to investigate the implications, if this radiation is assumed to come from the same Galactic center point source. It is quite clear that further extensive measurements at X- and γ-ray energies will be needed to clarify the nature of this source.

The continuum emission at MeV energies from interstellar space is the low-energy extension of the well-studied high-energy (~ 100 MeV) diffuse galactic gamma radiation (see, e.g., Mayer-Hasselwander *et al.* 1982). It is now generally agreed that the diffuse galactic γ-radiation above ~ 50 MeV mainly consists of three components: a π^0-decay component from nuclear interactions of cosmic-eay protons (and heavier nuclei) with interstellar matter, an electron-induced component which is produced as bremsstrahlung with interstellar matter, and to a smaller extent by inverse Compton collisions of the cosmic-ray-electrons with 2.7 K blackbody, infrared, and optical photons. At MeV energies the π^0-decay component can be neglected, leaving the electron-induced component as the only diffuse continuum source. Its observation allows the study of cosmic-ray electrons in interstellar space in an energy range (below 70 MeV) which is inaccessible to radio astronomy and to direct particle measurements (because demodulation theories are too uncertain to derive the demodulated spectrum in interstellar space).

New constraints on the continuum γ-radiation—both from the Galactic center source and the Galactic plane near the Galactic center—were derived from the data of the last 2.6 hr of a balloon flight with the MPE Compton telescope. A

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description of the telescope is given by Schönfelder, Graser, and Diehl (1982). The balloon flight took place on 1982 October 31, from Uberaba, Brazil. During this flight we observed the 1.8 MeV γ-ray line from radioactive ^{26}Al (Ballmoos, Diehl, and Schönfelder 1987*a*). A detailed description of the flight and the data analysis is given by Ballmoos, Diehl, and Schönfelder (1987*b*).

II. DATA ANALYSIS AND RESULTS

In a Compton telescope the measured information on the arrival direction of an incident γ-ray is transformed into so-called "event circles." The radius of an event circle on the sky is determined by the energy measurements in the two detectors of the telescope, and the center of each circle is determined by the measured direction of the scattered γ-ray. The MPE Compton telescope has a rather large field of view of about 60° FWHM near 1 MeV; however, it is possible to make the field much narrower by software restrictions on the events which are selected for the analysis. For the study of the Galactic center region only those events were analyzed that had event circles passing through an "acceptance circle" of $4\overset{\circ}{.}5$ radius around the Galactic center ($l = 0$, $b = 0$). By this selection the field of view of the telescope for accepted events is about 20° wide (FWHM) around 1 MeV, if the center is near the telescope axis (as was the case at the end of the balloon flight).

For the search of γ-ray emission from the Galactic plane a much wider field of view of the accepted events (accomplished by a larger acceptance radius around the Galactic center) should generally be of advantage. Actually, however, the signal-to-noise ratio becomes worse for event selections from a larger region; this is due to the special viewing geometry during the balloon flight (see Fig. 1 of Ballmoos, Diehl, and Schönfelder 1987*a*). During most of the balloon flight the more remote parts of the Galactic plane from the center were seen under large off-axis angles (low-detection efficiency), so that a widening of the analysis field of view mainly increases the background.

The background subtraction (instrumental, atmospheric, and diffuse cosmic) was performed according to the "mirror method" (Ballmoos, Diehl, and Schönfelder 1987*b*). This method is similar to the "on/off" technique applied in other spectral ranges. The mirror direction of the Galactic center has the same zenith angle as the Galactic center, but its azimuthal angle is rotated by 180°. (Note that the telescope was suspended from the balloon in such a way that the telescope axis always pointed toward the zenith. Therefore, the background response of the telescope was identical for the directions of source and mirror source.)

The background-subtracted energy-loss spectrum of γ-rays from the Galactic center region is shown in Figure 1. The energy interval 1.5–2.1 MeV was excluded in order to separate the contribution of the 1.8 MeV ^{26}Al γ-ray line from the continuum. Convolved sky-model spectra were fitted to the measured energy-loss spectrum. For this purpose the detection of celestial γ-rays in the telescope was simulated by a Monte Carlo program under actual balloon flight conditions. One sky model is given by a point source at $l = 0$, $b = 0$, the second model by extended emission along the Galactic plane as defined by the CO-distribution which was used by Clayton and Leising (1987) as tracer of supernovae in the Galaxy. This distribution has a full-width-half-maximum value of 120° around the Galactic Center. In both cases the photon number spectrum was assumed to be a power law with slope -2. The energy-loss spectra resulting from these two models had practically identical spectral shape, and therefore only one single model fit to the data is shown in Figure 1.

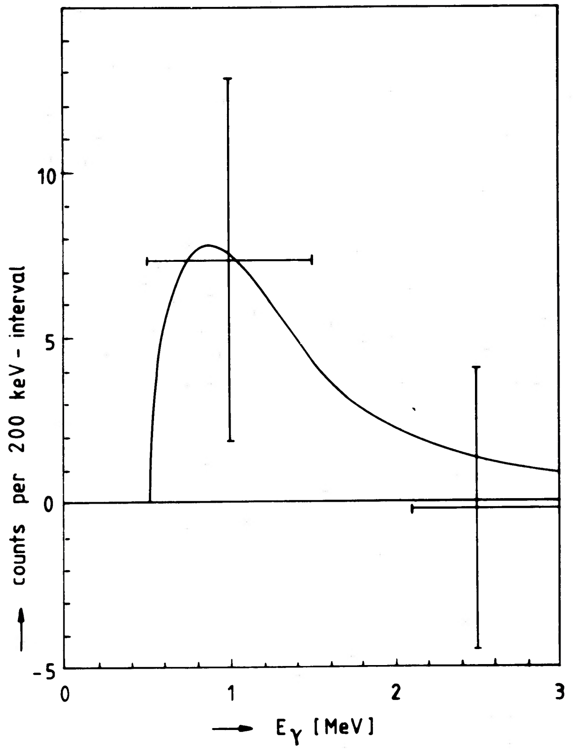

FIG. 1.—Comparison of the measured background-subtracted energy-loss spectrum of the Galactic center region (*two data points*) with the fit of a computer-simulated model spectrum from a point source model or an extended emission model along the Galactic plane (*solid line*).

The number of measured γ-rays between 0.6 and 3.0 MeV (excluding the 1.5–2.1 MeV interval) is 36, compared to 528 background events, yielding a statistical detection significance of only 1.1 σ. In the 1.6–2.0 MeV interval the fit of the model spectrum predicts 5.5 counts, which implies a 10% contribution of the total observed counts (54) and the ^{26}Al gamma-ray line interval, in agreement with the previous estimate of Ballmoos, Diehl, and Schönfelder (1987*a*).

The low statistical significance of the detection does not allow further investigations of whether the source of emission is pointlike or extended. It is, therefore, only possible to derive limits to the gamma-ray fluxes for both emission models. The conversion factors for transforming event counts into gamma-ray fluxes were obtained from the Monte Carlo simulation of the sky model spectra. For the Galactic center point source flux in the energy interval 0.6–3.0 MeV a 2 σ upper limit of 2.8×10^{-3} cm^{-2} s^{-1} is obtained. The corresponding limit to the total extended emission along the Galactic plane (diffuse emission plus unresolved sources normalized to the supernova source distribution throughout the galactic plane—as defined above—is 7.2×10^{-3} cm^{-2} s^{-1} rad^{-1} at $l = 0$ in the same energy interval.

III. DISCUSSION

a) Galactic Center Point Source

From the 2 σ upper limit to the point source flux we can conclude that the Galactic center was in a "low" intensity

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state during the time of our observation. This can be seen from Figure 2, which shows the energy spectrum of the Galactic center region as measured by *HEAO 3* (Riegler *et al.* 1985) at two different times (fall 1979 and spring 1980). Though the *HEAO 3* spectrometer with its 42° FWHM field of view actually measures the sum spectrum of all sources near the center, the intensity change by about a factor of 10 near 1 MeV within half a year implies the existence of a rather compact source (~ 0.2 pc). It is generally assumed that this source is the Galactic center itself; this speculation is based on the time variability argument only, and should be taken with care (see Introduction). Our upper limit (see Fig. 2) indicates that at the time of our observation the source was in a similarly low state as in spring 1980. The *HEAO 3* experimenters have fitted the spectrum by a four-component model which consists of a power-law spectrum, a three-photon continuum component from positronium decay, the 511 keV line, and a Comptonized thermal component which accounts for the MeV emission. The presently available observations (including ours) suggest that all four components are time-variable. However, correlation studies of the components and steady monitoring and more accurate location of all source components seem to be required to substantially improve our understanding of the central source. In this sense, our new upper limit may be regarded as one further mosaic stone of the still unsolved puzzle.

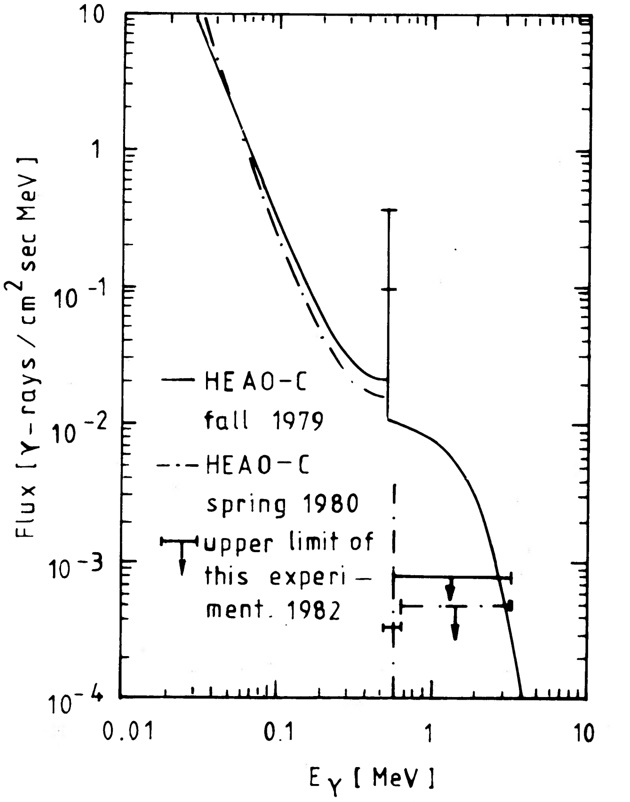

FIG. 2.—Spectrum of the Galactic center region as measured by *HEAO 3* (Riegler *et al.* 1985) at two different times. The data point in the ~ 0.5 to 0.7 MeV interval represents the spring 1980 observation of *HEAO 3.* Our 2 σ upper limit to the 0.6–3.0 MeV interval is indicated.

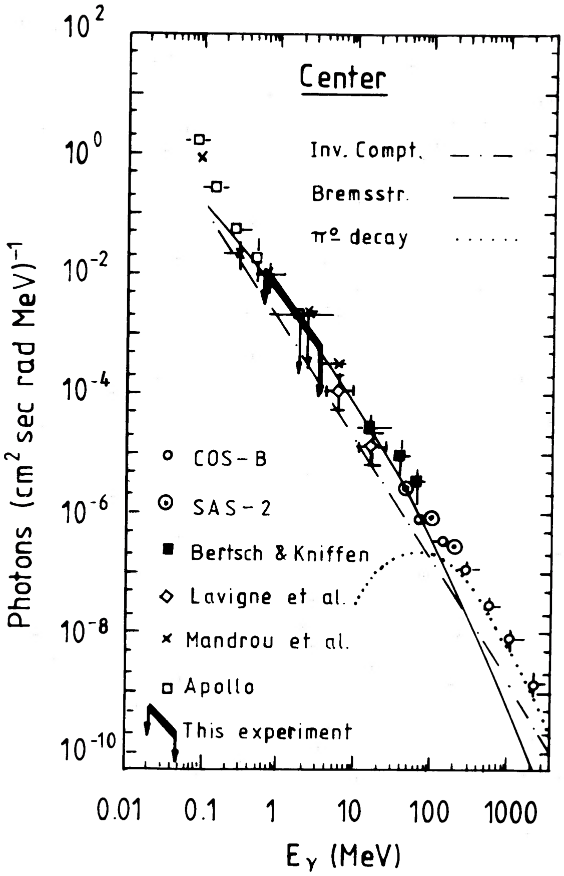

FIG. 3.—Broad-band gamma-ray emission of the Galactic plane from the Galactic center region. *COS B* data are from Paul *et al.* (1978), *SAS 2* data are from Kniffen and Fichtel (1981); the results of Mandrou *et al.* (1980), Bertsch and Kniffen (1983), and Lavigne *et al.* (1986) are from balloon experiments. The 2 σ upper limits from our 0.6–3.0 MeV measurement are indicated. The best-fit, three-component model of Sacher and Schönfelder (1984) is based on their "high" cosmic-ray electron spectrum and a confinement time of cosmic-ray electrons in the Galaxy of 2.5×10^7 yr.

b) Diffuse Emission from the Central Part of the Galactic Plane

Figure 3 contains a compilation of measurements of the diffuse gamma radiation between 100 keV and 2 GeV from the Galactic plane in the center region. Actually, the contribution of unresolved sources to this diffuse component is rather uncertain, and below 35 MeV the spectrum shown certainly includes the total diffuse emission along the plane plus unresolved sources. Our limit between 0.6 and 3.0 MeV is perfectly consistent with the other measurements at lower and higher energies. Sacher and Schönfelder (1984) had tried to interpret all measurements that were available at that time in the broad spectral range between 100 keV and 2 GeV by a three-component model consisting of a π^0-decay, a bremsstrahlung, and an inverse Compton component (neglecting a possible contribution from unresolved sources). In the three-component model of Sacher and Schönfelder most of the γ-rays in the 0.6–3.0 MeV range are produced by bremsstrahlung of electrons with energies between about 1 and 10 MeV. From these models the one which fits our upper limit (and the rest of the data) best is shown in Figure 3 as well. This best-fit model is based on a local interstellar cosmic-ray electron spectrum with a power-law slope of -2.8 between 60 and 1000 MeV, and -1.8 below 60 MeV (See Fig. 4). The 1–10 MeV interstellar cosmic-ray electron spectrum of this best-fit model is described by

$$40E_{\rm MeV}^{-1.8}\ \text{electrons cm}^{-2}\ \text{s}^{-1}\ \text{MeV}^{-1}\ \text{sr}^{-1}\ ,$$

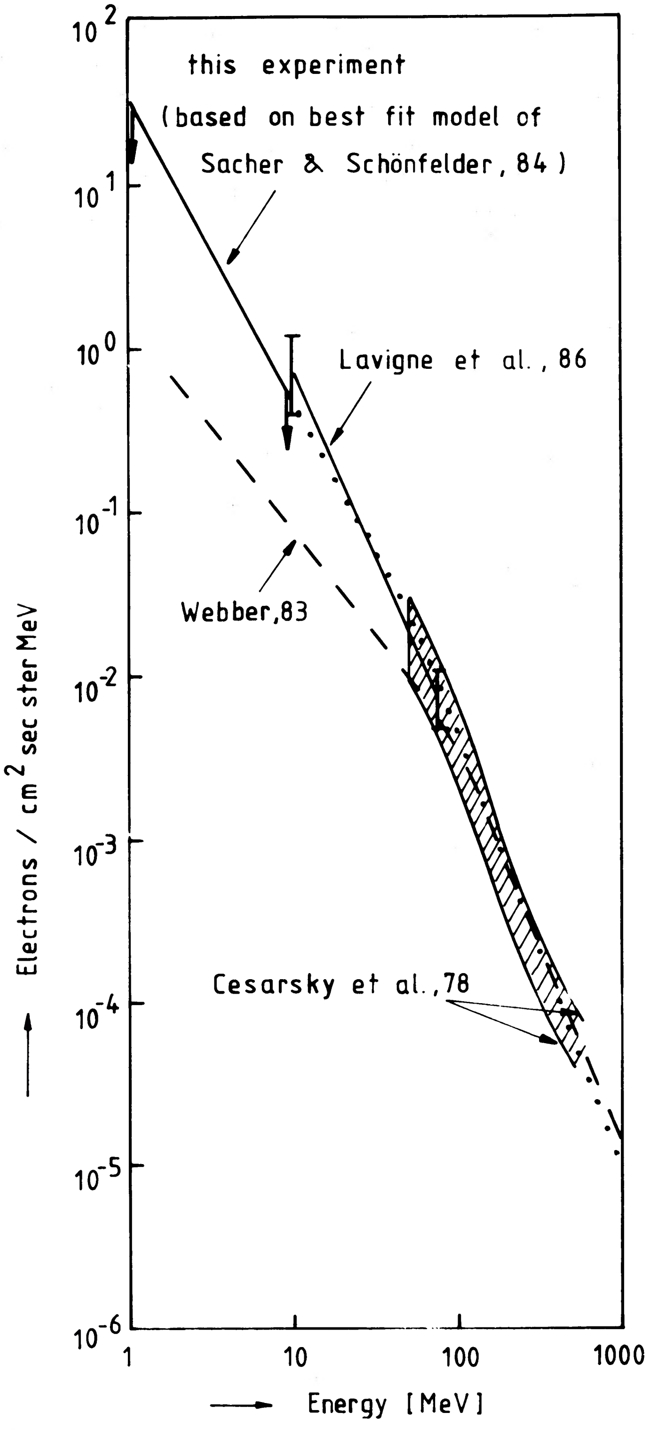

FIG. 4.—Local interstellar cosmic-ray electron spectrum between 1 and 100 MeV. The constraints derived by our measurements in the 1–10 MeV range (labeled "this experiment") are compared with other experimental and theoretical results. The dotted line is the extension of the best-fit model of Sacher and Schönfelder (1984) above 10 MeV.

nicely overlapping with the one derived by Lavigne *et al.* (1986) in the interval 12 MeV–75 MeV ($160E_{\mathrm{MeV}}^{-2.3}$ electrons cm^{-2} s^{-1} MeV^{-1} sr^{-1} between 12 and 75 MeV). Furthermore, both electron spectra well connect to the range of possible energy spectra which are consistent with the *SAS 2* gamma-ray data above 35 MeV (Cesarsky, Paul, and Shukla 1978).

It should be well understood that the electron intensity spectrum derived above for the 1–10 MeV interval can only be an upper limit to the real interstellar cosmic-ray electron spectrum in this spectral range: first, because it was derived from an upper limit of the gamma-ray measurements, and second, because the existence of possible unresolved discrete gamma-ray sources or unresolved γ-ray lines in the center part of the Galactic plane was ignored. Indeed, Webber (1983) suggests that the actual interstellar cosmic-ray intensity below 10 MeV is about an order of magnitude lower than the upper bound to the spectrum derived above (see Fig. 4). Webber's prediction is based on a slope of the electron spectrum of −2.3 between 100 and 1000 MeV, and a slope of −1.3 below 100 MeV.

Further study of the continuum gamma radiation at MeV energies from the Galactic center region needs observations with a sensitivity much higher than could be obtained during the short balloon flight discussed in this paper. Such observations will be performed by COMPTEL (Schönfelder *et al.* 1984) onboard the NASA Gamma Ray Observatory (GRO) in the near future.

We would like to thank the National Scientific Balloon Facility in Texas and the Institute de Pesquisas Espacials (INPE) in Brazil for conducting the balloon flight under very difficult conditions. We are grateful to U. Graser, W. Hofmeister, N. Huber, L. Pichl, and F. Schrey from the Max-Planck-Institute for the assistance in our balloon telescope project. One of us (P. v. B.) is indebted to the European Space Agency for an external fellowship award.

REFERENCES

Ballmoos, P., Diehl, R., and Schönfelder, V. 1987*a*, *Ap. J.*, **318**, 654.
———. 1987*b*, *Ap. J.*, **312**, 134.
Bertsch, D. L., and Kniffen, D. A. 1983, *Ap. J.*, **270**, 305.
Cesarsky, C., Paul, J. A., and Shukla, P. G. 1978, *Adv. Space Sci.*, **59**, 73.
Clayton, D. D., and Leising, D. M. 1987, *Phys. Rept.*, **144**, 1.
Gilman, D., Metzger, A. E., Parker, R. H., Trombka, J. I. *et al.*, 1978, NASA TM 79619, p. 190.
Kawai, N., *et al.* 1988, *Ap. J.*, **330**, 130.
Kniffen, D. A., and Fichtel, C. E. 1981, *Ap. J.*, **250**, 389.
Lavigne, J. M., Mandrou, P., Niel, M., Agrenier, B., Bonfand, E., and Parlier, B. 1986, *Ap. J.*, **308**, 370.
Leventhal, M., MacCallum, C. J., and Stang, P. D. 1978, *Ap. J.* (*Letters*), **225**, L11.
Levine, A., *et al.* 1979, *Bull AAS*, **11**, 429.
Mandrou, P., Bul-Van, A., Vendrenne, G., and Niel, M. 1980, *Ap. J.*, **237**, 424.
Matteson, J. L. 1982, in *Proc. of AIP Conf. 83, The Galactic Center*, ed. G. R. Riegler and R. D. Banford, (NY: AIP), p. 109.
Mayer-Hasselwander, H., *et al.* 1982, *Astr. Ap.*, **105**, 164.
Paul, J. A., *et al.* 1978, *Ap. J.* (*Letters*), **63**, L31.
Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., and Jacobson, A. S. 1985, *Ap. J.* (*Letters*), **294**, L13.
Riegler, G. R., Ling, J. C., Mahoney, W. A., Wheaton, W. A., Willet, J. B., and Jacobson, A. S. 1981, *Ap. J.* (*Letters*), **248**, L13.
Sacher, W., and Schönfelder, V. 1984, *Ap. J.*, **279**, 817.
Schönfelder, V., Graser, U., and Diehl, R. 1982, *Astr. Ap.*, **110**, 138.
Schönfelder, V., *et al.* 1984, *IEEE Trans.*, **NS31**, 766.
Skinner, G. K., *et al.* 1987, *Nature*, **330**, 544.
Watson, M. G., Willingale, R., Grindlay, J. E., and Hertz, P. 1981, *Ap. J.*, **250**, 142.
Webber, W. R., 1983, in *Composition and Origin of Cosmic Rays*, ed. M. M. Shapiro (Dordrecht: Reidel), p. 83.

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