# ANNIHILATION RADIATION AND GAMMA-RAY CONTINUUM FROM THE GALACTIC CENTER REGION

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ABSTRACT. Observations of the time-dependent, electron-positron annihilation line radiation and gamma-ray continuum emission from the region of the Galactic Center show that there are two components to the annihilation line emission: a variable, compact source at or near the Galactic Center, and a steady, diffuse interstellar distribution. We suggest that the annihilating positrons in the compact source, observed from 1977 through 1979, result from photon-photon pair production, most likely around an accreting black hole, and that the annihilating, interstellar positrons result from the decay of radionuclei produced by thermonuclear burning in supernovae.

## 1. Introduction

Positron annihilation radiation is an important component of the high energy spectra of a wide range of astrophysical sources — from solar flares and gamma-ray bursts to the interstellar medium, the Galactic Center, and apparently even active galactic nuclei (see e.g. Ramaty and Lingenfelter 1982 and Lingenfelter 1988). The intense emission from the region of the Galactic Center is, in fact, the most luminous steady source of annihilation radiation known — emitting more than $10^4$ $L_\odot$ in annihilation radiation alone.

Here, we review in detail the observations and interpretations of the time-dependent, electron-positron annihilation line radiation and gamma-ray continuum emission from the region of the Galactic Center. First, we discuss the evidence for two distinct positron sources: a variable, compact source and a steady, diffuse galactic disk source. Then we discuss the evidence for temporally associated x-ray and gamma-ray continuum emission and the question of the location of the compact source. Finally, we consider the implications



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of the observations on the nature of the positron annihilation region, and the positron production processes in both the compact source and the galactic disk, and the general nature of the compact source – and whether it might be an accreting black hole.

## 2. Observations of Annihilation Radiation

Positron annihilation radiation from the region of the Galactic Center has been observed since 1970. It was first measured by Haymes et al. (1975; see also Johnson, Harnden and Haymes 1972; Johnson and Haymes 1973) from Rice University with low resolution NaI instruments in a series of three balloon flights in Brazil (see Figure 1). A spectral feature at 476±24 keV was indicated by the first two of these observations. But this feature appeared to be shifted in the third observation to a peak at 530±11 keV. It was not until 1977 that the annihilation line was clearly identified at an energy of 510.7±0.5 keV by observations with a high resolution Ge instrument flown in Australia by Leventhal et al. (1978) from the Bell and Sandia Laboratories. These observations showed that the line is very narrow (FWHM < 3.2 keV) and that the continuum below 511 keV contains a significant contribution from orthopositronium annihilation. It was in fact suggested (Leventhal 1973) prior to this high resolution observation that the shifted peak at 476 keV could result from the convolution of the broad response function of the Rice University detector with a Galactic Center spectrum

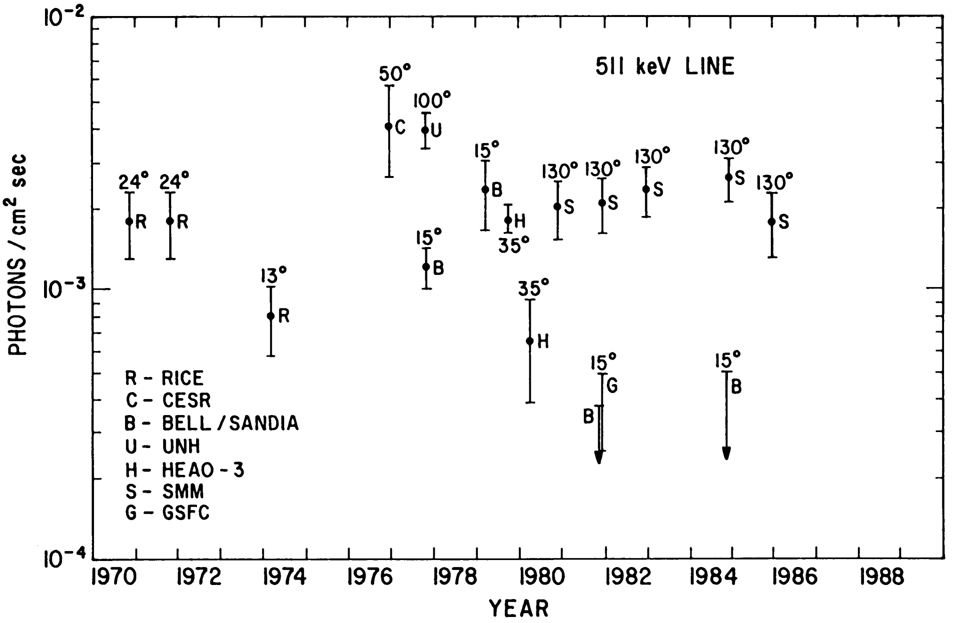


**Figure 1.** Observations of the 511 keV annihilation radiation from the direction of the Galactic Center *versus* time and detector field of view (FWHM in degrees, indicated above each data point), showing evidence for two components: a steady diffuse galactic source and a variable, compact source. The Rice (R) data includes positronium continuum.

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consisting of a narrow line and the accompanying orthopositronium continuum. This interpretation of the early Rice University data still seems valid, and we find that orthopositronium continuum probably accounted for 50% of the reported line flux in 1970 and 1971. The subsequent shift of the reported peak to 530 keV in 1974 may result from a similar convolution of increased emission >511 keV.

Subsequent observations by Riegler et al. (1981, 1985) from the Jet Propulsion Laboratory in the fall of 1979 and spring of 1980 with a Ge spectrometer on the HEAO-3 satellite also detected the 511 keV line. As can be seen in Figure 1, these observations provided, for the first time, strong evidence that the line flux varies with time, decreasing from $(1.85\pm0.21)\times10^{-3}$ photons/cm$^2$ sec in the fall to $(0.65\pm0.27)\times10^{-3}$ photons/cm$^2$ sec in the spring. This variability in the line flux is particularly significant since it was established by observations with the same instrument.

These detailed measurements of the spectral variation in both the line and the continuum, as can be seen in Figures 2, show not only the decrease of a factor of 3 in the annihilation line flux, but also the simultaneous decrease of a factor of > 10 in the > 511 keV continuum flux, while the inferred orthopositronium flux remained essentially constant. We will discuss these aspects in the following section.

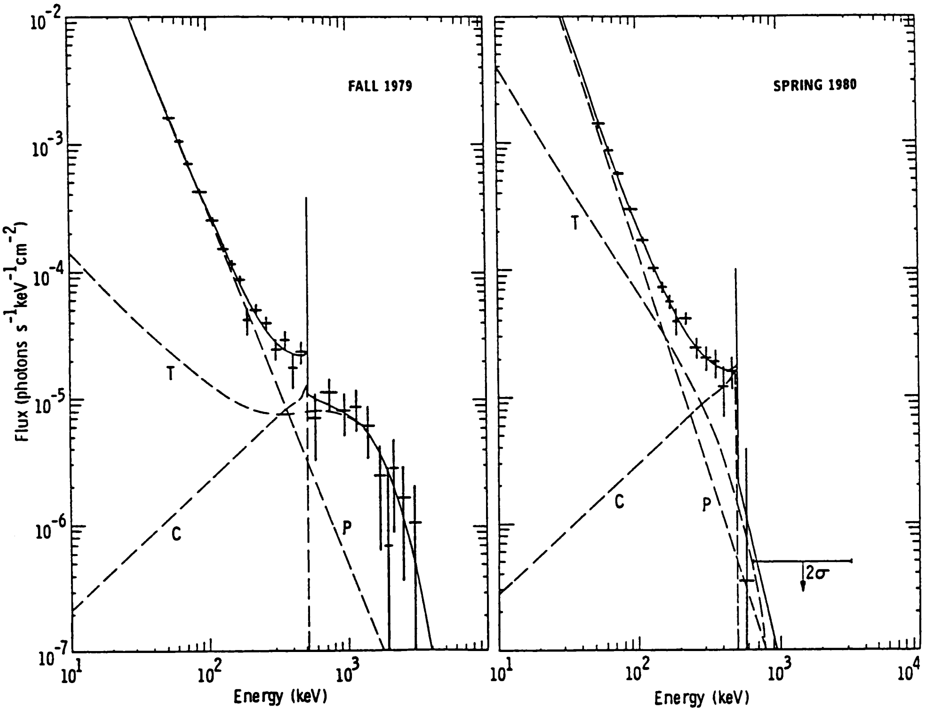


**Figure 2.** HEAO-3 measurements of the Galactic Center region 511 keV annihilation line and gamma-ray continuum fluxes in the fall of 1979 and the spring of 1980, together with best fits (Riegler et al. 1985) of the spectra to an orthopositronium continuum (curve C), a low energy power law (P), and a Comptonized thermal component (T).

The variable nature of the positron annihilation line flux was confirmed by independent Ge detector observations (Leventhal et al. 1980, 1982, 1986; Paciesas et al. 1982). The most significant of these are the observations carried out by the Bell/Sandia group from 1977 to 1984, since they also allow the comparison of data from essentially the same instrument. These observations yielded 511 keV line fluxes of $(1.22\pm0.22)\times10^{-3}$ photons/cm$^2$ sec in November 1977 (Leventhal et al. 1978) and $(2.35\pm0.71)\times10^{-3}$ photons/cm$^2$ sec in April 1979 (Leventhal et al. 1980) and $1\sigma$ upper limits of $< 0.38\times10^{-3}$ photons/cm$^2$ sec in November 1981 (Leventhal et al. 1982) and $< 0.48\times10^{-3}$ photons/cm$^2$ sec in November 1984 (Leventhal et al. 1986). Thus, there is clear indication that the 511 keV line flux decreased after 1979 and marginal evidence for an increase in flux from 1977 to 1979.

These time-varying observations clearly require a variable, compact source for at least part of the annihilation line emission from the Galactic Center region. The time scale of the variation, less than 1/2 year, implies that the annihilation radiation was produced in a region less than 1/2 light year in diameter. The fall 1979 observations also indicate that the direction of this source is within 4° of the Galactic Center. As we have argued before (Ramaty and Lingenfelter 1981; Lingenfelter and Ramaty 1982), the positrons responsible for the observed variable annihilation radiation were most likely produced by a single object, probably a black hole.

In addition to these measurements, there were two other very wide angle observations of the 511 keV line prior to 1979 (see Figure 1): a Ge detector observation with a 50° field of view (FWHM) by Albernhe et al. (1981) from Saclay and Toulouse, and a NaI detector observation with a 100° field of view by Gardner et al. (1982) from the University of New Hampshire. As can be seen, the flux measured in the latter observation was significantly higher than that measured just 10 days earlier by Leventhal et al. (1978) with the Bell/Sandia detector which had a much smaller, 15° field of view. This difference suggested a direct correlation between the measured flux and the detector field of view, as was first pointed out by Dunphy, Chupp and Forrest (1983).

This correlation is even more clearly demonstrated by a comparison of the observations of Share et al. (1988) with the 130° field-of-view, NaI detector on the SMM satellite and the upper limits of Leventhal et al. (1982, 1986), and Paciesas et al. (1982) with 15° field-of-view detectors in late 1981 and 1984 (see Figure 1). Since the SMM detector points continuously at the Sun, the Galactic Center passes through its field of view once a year. Searching for a yearly modulation in the data, the SMM observers were able to separate a 511 keV feature of astronomical origin from the copiously produced 511 keV emission in the atmosphere, the satellite and the detector. They found annihilation line fluxes of (1.75 to 2.55)$\times10^{-3}$ photons/cm$^2$ sec for emission from a point source during different annual passages of the Galactic Center through the 130° field of view of the detector. There is no data for the December 1983 passage because the instrument was not fully operational just prior to the repair of SMM in space in early 1984. For the other five passages the 511 keV line flux has not varied by more than 30% from year to year and is consistent with single average value of $(2.1\pm0.4)\times10^{-3}$ photons/cm$^2$ sec. This flux is roughly a factor of four higher than the $1\sigma$ upper limits set by Leventhal et al. (1982, 1986) and Paciesas et al. (1982) during the same period with much narrower, 15° field-of-view detectors.

This disparity in observations between detectors with wide and narrow fields of view, strongly suggests that the bulk of the emission observed with SMM is spatially distributed.

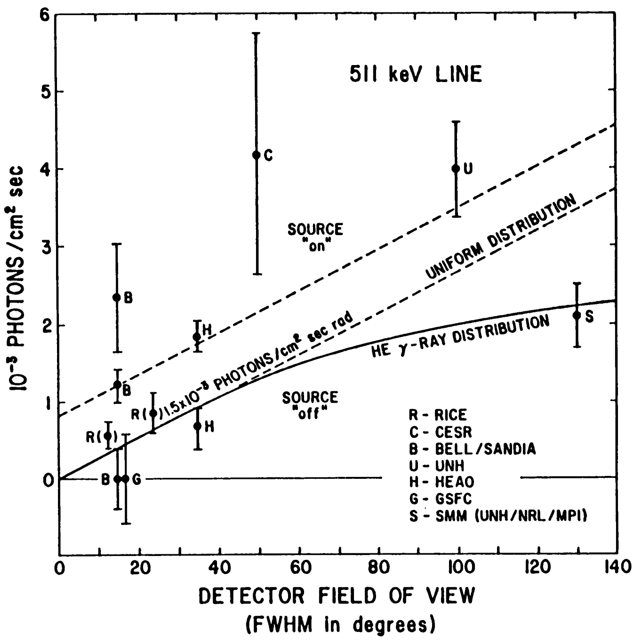


**Figure 3.** Measured 511 keV annihilation line emission from the direction of the Galactic Center *versus* the detector field of view. The dashed lines and solid curve represent the contributions of the diffuse component. (Modified from Dunphy, Chupp and Forrest 1983).

The existence of a spatially distributed galactic 511 keV line emission with a flux of $(1.5 \pm 0.3) \times 10^{-3}$ photons/cm$^2$ sec per radian of galactic longitude in the direction of the Galactic center was suggested (Dunphy, Chupp and Forrest 1983) previously from measurements up to 1980. The later SMM measurements are also quite consistent with such a flux from the direction of the Galactic Center, if the emission has a longitudinal distribution similar to that of the high energy (>70 MeV) gamma-ray emission measured with COS-B (Mayer-Hasselwander et al. 1980), as can be seen from the solid curve in Figure 3. The Rice (R) data in this figure are corrected for orthopositronium, as discussed above. Very similar galactic 511 keV line fluxes of $(1.6 \pm 0.3) \times 10^{-3}$ photons/cm$^2$ sec rad and $(1.35 \pm 0.22) \times 10^{-3}$ photons/cm$^2$ sec rad in the direction of the Galactic Center were found from SMM (Share et al. 1988) and HEAO-3 (Mahoney 1988) observations, respectively, assuming that the annihilation radiation is produced with a galactic distribution similar to that of the molecular (CO) gas.

Thus we see that the 511 keV line observations require both a highly variable, compact source of positrons, active from 1977 through 1979, and a steady, diffuse galactic positron source with a flux of $\sim 1.5 \times 10^{-3}$ photons/cm$^2$ sec rad in the region of the Galactic Center and a spatial distribution similar to that of the galactic molecular gas or the high energy gamma-ray emission, as we previously suggested (Ramaty and Lingenfelter 1987).

The time dependence of the 511 keV line emission from the compact source can be seen much more clearly in Figure 4 (center panel). There we show the effective compact source flux, determined by subtracting the diffuse contribution, estimated in Figure 3, from the observed flux. As can be seen, 511 keV annihilation line emission of more than $3\sigma$ significance has been observed (B, U and H) from the compact source only during the years 1977 – 1979. This compact source has an annihilation line luminosity, reaching $\sim 1 \times 10^{37}$ erg/sec, assuming that the compact source is at a nominal distance of 8.5 kpc. The diffuse galactic component is the most luminous steady source of annihilation line emission known with a luminosity of $\sim 4 \times 10^{37}$ erg/sec, or fully $10^4$ $L_\odot$ in annihilation radiation alone.

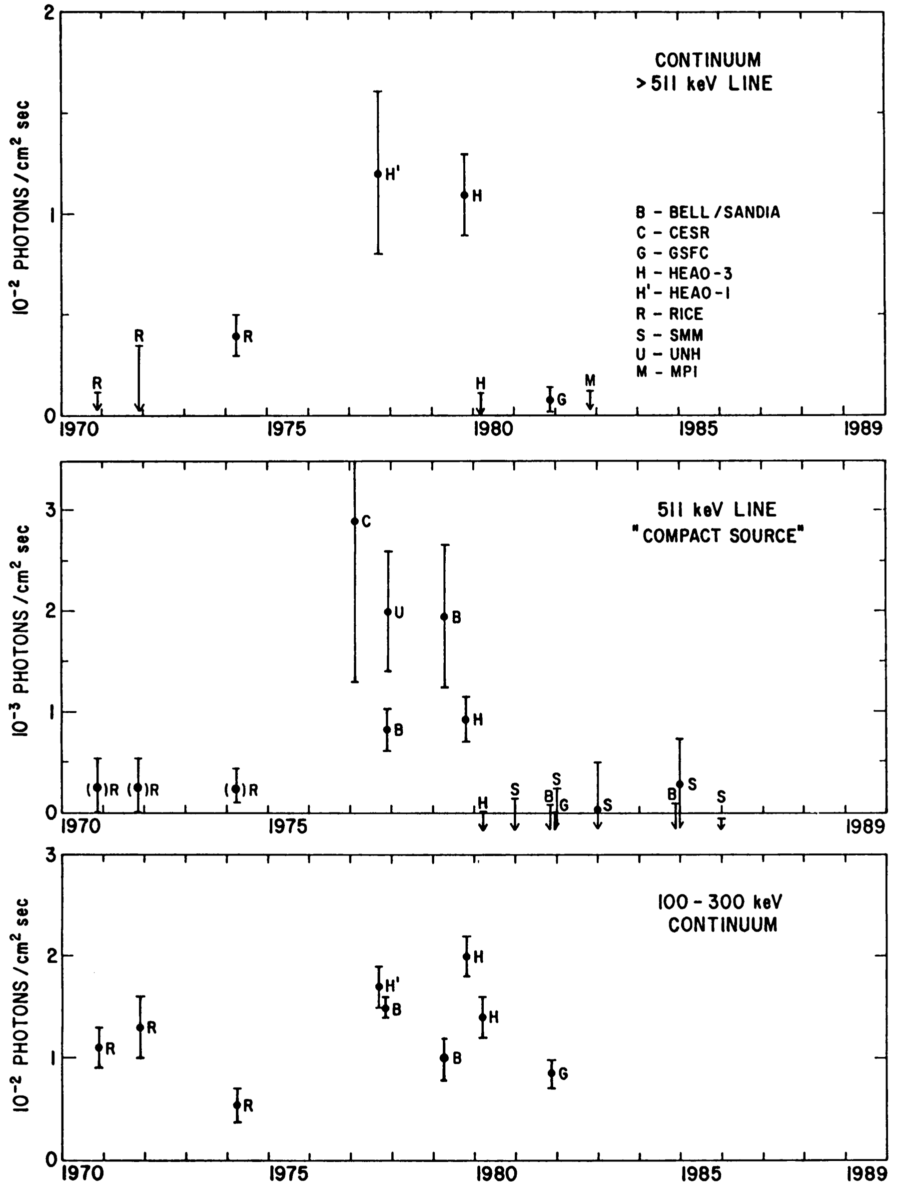


**Figure 4.** The time dependence of the 511 keV line emission from the compact source (center panel, with the diffuse galactic contribution subtracted) together with that of the gamma-ray and hard x-ray continuum, showing the strong correlation between the variation in the 511 keV line flux and that in the > 511 keV continuum.

### 3. The Gamma-Ray and Hard X-Ray Continuum

The observations of the gamma-ray and hard x-ray continuum from the Galactic Center region (Figure 4) also show signficant variations in time. Moreover, the variations in the continuum flux at energies $> 511$ keV appear to be strongly correlated with those of 511 keV annihilation line. As can be seen in Figures 2 and 4, the most striking evidence for a correlation between the $> 511$ keV continuum and the 511 keV line fluxes is in the HEAO-3 observations (Riegler et al. 1985). The same Ge detectors, which measured the 511 keV line in the fall of 1979 and spring of 1980, also measured the continuum from $\sim 50$ keV to $\sim 3$ MeV. The angular resolution of this detector was $\sim 35°$. As can be seen, the continuum flux at energies $> 511$ keV decreased by more than a factor of 10 from $1.1 \times 10^{-2}$ photons/cm$^2$ sec in the fall, to a $1\sigma$ upper limit of $< 1 \times 10^{-3}$ photons/cm$^2$ sec in the spring of 1980, at the same time that the 511 keV line flux decreased by about a factor of 3. The 511 keV line flux measured by HEAO-3 in the spring of 1980 is entirely consistent with that expected from the diffuse galactic component alone, so that the residual flux from the compact source at that time is $(-0.27 \pm 0.27) \times 10^{-2}$ photons/cm$^2$ sec. This correlation between the variation in the continuum flux at energies $> 511$ keV and that in the 511 keV line flux, strongly suggests that both fluxes originate in the same compact source.

As can also be seen in Figure 4, a comparably high continuum flux $> 511$ keV was also found (Matteson 1982) in the fall of 1977 by the HEAO-1 detectors during roughly the same time that high 511 keV line fluxes were observed by the Bell/Sandia and University of New Hampshire balloon experiments. No significant continuum flux $> 511$ keV has been observed at other times, except perhaps 1974, when no significant 511 keV line flux was observed.

Assuming that the compact continuum source is also at a nominal distance of 8.5 kpc, the luminosity of the $> 511$ keV continuum was $(2.0 \pm 0.4) \times 10^{38}$ erg/sec when the source was active in the fall of 1979. Comparing this luminosity with that of the 511 keV line of $\sim 10^{37}$ erg/sec during that same period, we see that the ratio of the positron annihilation line luminosity to that of the $> 511$ keV continuum, $L_{e+}/L_{>511} \sim 0.05$. As we shall show, this ratio sets very severe constraints on the possible origin of the annihilating positrons.

At much higher energies, in the 100 MeV to 1 GeV range, gamma-ray continuum emission has also been observed (Swanenburg et al. 1981) from the region within 300 pc of the Galactic Center at a luminosity of $\sim 10^{37}$ erg/sec, but no variability has been reported in this energy range.

At energies $< 511$ keV the continuum is also quite variable. However, as we saw in Figure 2, the three-photon orthopositronium continuum shows no significant variation between the fall of 1979 and the spring of 1980. The best fit (Riegler et al. 1985) to the HEAO-3 data gave virtually the same positronium continuum flux at both times. Moreover, the same flux per radian was also consistent with the other measurements (Gardner et al. 1982, Leventhal et al. 1978, 1982, Brown and Leventhal 1987) in the fall of 1977 and spring of 1979, and with the 1970-71 observations (Johnson and Haymes 1973), assuming that positronium annihilation was the cause of the apparent shift of the line center as suggested by Leventhal (1973).

This can be seen in Figure 5, where we show the observed three-photon orthopositronium continuum fluxes, determined from the measured 511 keV line fluxes and the associated positronium annihilation fractions. The continuum fluxes versus the detector fields of view, shown in the upper panel, are in fact quite consistent with a single diffuse galactic component, having the same longitudinal distribution as that of the diffuse 511 keV line component (Figure 3), and a flux of $6.75\times10^{-3}$ photons/cm$^2$ sec rad, which would be expected from the diffuse galactic 511 keV line flux of $1.5\times10^{-3}$ photons/cm$^2$ sec rad, if all of the annihilation occured via positronium formation. These observations do not show any significant evidence for an excess variable contribution from a compact source, unlike what was seen with the 511 keV line.

The continuum fluxes measured per radian of galactic longitude are also clearly consistent with a constant diffuse flux, as can be seen in the lower panel. This constancy of the orthopositronium continuum suggests that it, in fact, comes solely from the diffuse galactic component of the annihilation radiation. Furthermore, the weighted mean flux of $(6.7\pm1.6)\times10^{-3}$ photons/cm$^2$ sec rad, determined from these measurements, is almost exactly equal to the $6.75\times10^{-3}$ photons/cm$^2$ sec rad, expected from the diffuse galactic 511

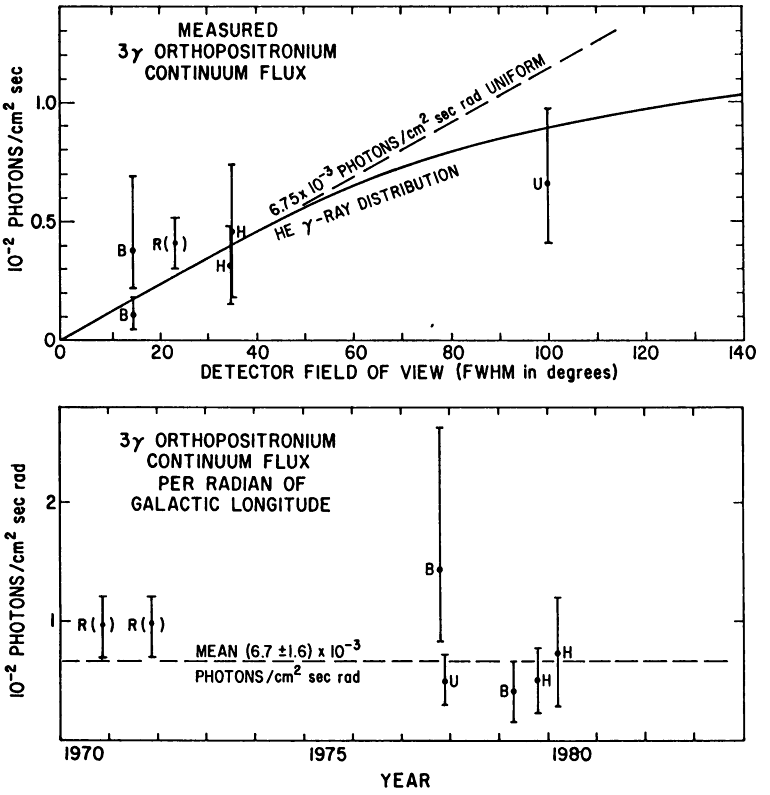


**Figure 5.** The measured orthopositronium continuum fluxes *versus* the detector fields of view and dates of observations, showing that they can be entirely accounted for by a constant diffuse component without any excess, variable contribution from the compact source.

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keV line flux of $1.5\times10^{-3}$ photons/cm$^2$ sec rad, if all of the annihilation occured via positronium formation. Although in a neutral medium the fraction of positrons annihilating via positronium has been measured (Brown, Leventhal and Mills 1986) to be $\sim 0.9$; this fraction can reach 1 in a partially ionized gas (Bussard, Ramaty and Drachman 1979). Since the 511 keV line flux measured in the spring 1980 by HEAO-3 was also entirely consistent with that expected from the diffuse galactic component, the ratio of the 511 keV line to orthopositronium continuum fluxes also implies that the fraction of positrons annihilating via positronium is $1.0\pm0.1$ in the diffuse galactic component.

The lack of a significant variation in the orthopositronium continuum flux associated with the variations in the 511 keV line flux from the compact source also implies that the fraction of positrons annihilating via positronium in that source is $\ll 1$. This differs from the conclusion of Brown and Leventhal (1987), who also reviewed the measurements of the positronium fraction, but they did not take into account the contribution of the diffuse flux to the observations of the region of the Galactic Center. We will discuss the implications of these ratios in detail below.

At energies less than about 300 keV where the orthopositronium continuum is only a small part of the observed continuum, there is no obvious indication of a correlation between the continuum and the 511 keV line fluxes, as can be seen in Figure 4. The continuum measured by the HEAO-3 decreased by only $\sim 30\%$ in the 100 to 300 keV band during the same 6 months that the 511 keV flux decrease by a much larger fraction. Moreover, the Bell/Sandia measurements (Leventhal et al. 1978, 1980) are anticorrelated, if anything, showing a factor of 2 decrease from the fall of 1977 to the spring of 1979, while the 511 keV line flux increased.

Much of the variability in the 100–300 keV range, however, results from the fact that at these energies there are several, intense, variable sources within the field of view of the detectors, as has been shown by the HEAO-1 measurements (Knight et al. 1985, Levine et al. 1984). This leads us to the problem of which of these sources, if any, is the compact source of the annihilating positrons and $> 511$ keV continuum.

## 4. The Position of the Compact Source

Although the compact source of 511 keV annihilation radiation is in the direction of the Galactic Center and is truly unique in our galaxy, we do not know whether it is actually located at the Galactic Center or just nearby. An accurate determination of the position of this source remains a major problem.

The only direct measurement (Riegler et al. 1981) of the position of the 511 keV line source, when it was active, was that made by the HEAO-3 detectors in a galactic plane scan during the fall of 1979. This measurement, shown in Figure 6, gives a point source centroid position of galactic longitude $l^{II} = 3.9\pm4.0°$, assuming $b^{II} = 0°$. This only constrains the source to be within about half a kpc of the Galactic Center.

Several distinct sources have been identified within this region at x-ray energies which may include the compact source. The most intense source at 13–180 keV identified in the HEAO-1 measurements (Levine et al. 1984, Knight et al. 1985) from August 1977 through January 1979, while the compact source of annihilation radiation was active, was a "Galactic Center" source GCX (1742-294) at $l^{II} \approx -0.4°$ and $b^{II} \approx -0.4°$. This and two other sources, GX 1+4, and GX 5-1, whose intensities each varied by as much as a factor of three during this period, accounted for the nearly all of the variable, measured flux above $\sim$ 100 keV. The source GCX also had the hardest spectrum, observed to be $\propto E^{-2.12}$ over the range 13–180 keV in September 1978, and at an assumed distance of 10 kpc it was the most luminous persistent hard x-ray source in the Galaxy, with a luminosity of $\sim 2\times10^{38}$ ergs/sec in that energy band.

Now, however, recent observations with imaging detectors on Spacelab 2 at 3–30 keV in 1985 (Skinner et al. 1987) and on a balloon at >35 keV in 1988 (Cook et al. 1988) show that during the past few years, when the compact source of positrons was not active, the most intense source at 30 keV and above is that known as 1E1740.7-2942 at $l^{II} \approx -0.9°$ and $b^{II} \approx -0.1°$ with a luminosity of $\sim 2\times10^{37}$ ergs/sec in the energy band from 35 to 200 keV (Cook et al. 1988).

We do not know, however, whether either of these sources is also the compact source of the positron annihilation radiation, and unfortunately we will not know for certain until that source is detected again and its position is accurately measured.

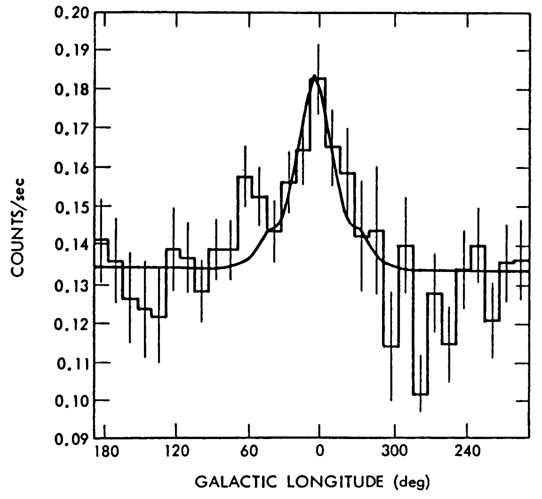


**Figure 6.** 511 keV line flux from the HEAO-3 scan of the galactic plane in the fall of 1979, showing the instrumental response for a point source centered at $l^{II} = 3.9\pm4.0°$, from Riegler et al. (1981).

## 5. The Nature of the Compact Source

We consider first the annihilation region around the compact source in which the variable 511 keV annihilation line emission is produced and then turn to the source of the annihilating positrons and > 511 keV gamma-ray continuum.

### 5.1 THE ANNIHILATION REGION

The nature of the compact, positron annihilation region is constrained by the observed intensity variations, width and centroid of the 511 keV line. The observed (Riegler et al. 1981, 1985, Leventhal et al. 1982) flux variations require that the size of the annihilation region must be $< 10^{18}$ cm and that the mean density of gas must be $> 10^5$ H/cm$^3$, so that the positrons can slow down and annihilate in less than half a year.

The measured (Leventhal et al. 1978, Riegler et al. 1981) 511 keV line width (FWHM $<$ 2.5 keV) requires a gas temperature in the annihilation region less than $5\times10^4$ K and the line width also limits any velocities of rotation, expansion or random motion to < 700 km/sec. The measured line centroid of 510.90±0.25 keV, compared to the rest energy of 511.003, requires a bulk velocity in the line of sight of $-90 < v < +200$ km/sec and a gravitational redshift $z < 7\times10^{-4}$. These constraints are summarized in Table 1. Such conditions appear to exist (e.g. Lacy et al. 1980) within the central parsec of the Galaxy. The further effects of these constraints on the size of the annihilation region as a function of the possible mass of a central compact source are shown in Figure 7.

**Table 1. Constraints on the Compact Annihilation Region**

| PHYSICAL PARAMETER | CONSTRAINT | OBSERVATION |
|---|---|---|
| Size | $< 10^{18}$ cm | Variability |
| Gas Density | $> 10^5$ H/cm$^3$ | Variability |
| Temperature | $\leq 5\times10^4$ K | Line Width |
| Rotation, Expansion or Random Motion | < 700 km/sec | Line Width |
| Bulk Motion in Line of Sight | $-90 < v < +200$ km/sec | Line Centroid |
| Gravitational Redshift | $z < 7\times10^{-4}$ | Line Centroid |

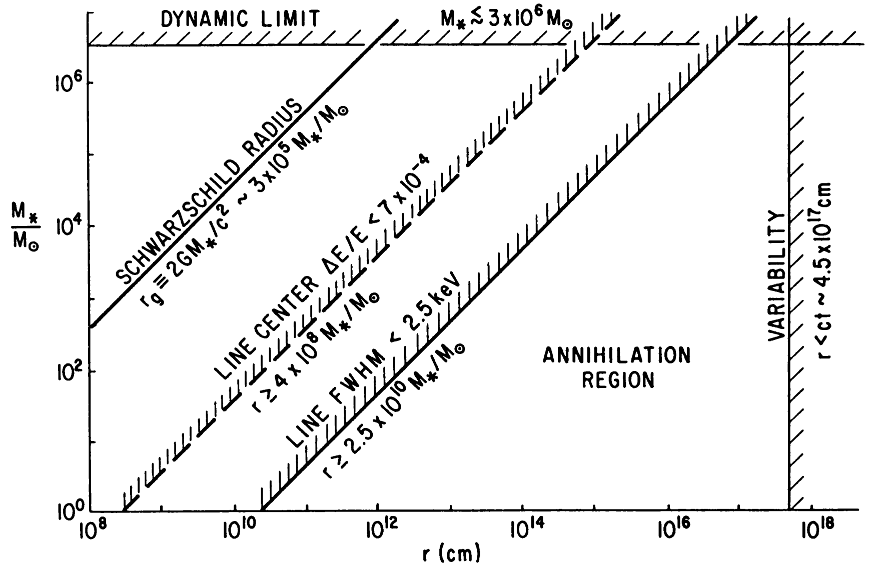


**Figure 7.** Constraints on the size of the annihilation region around a compact source of mass $M_*$.

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The apparent lack of a detectable orthopositronium continuum (Riegler et al. 1985) associated with the variable 511 keV line emission, also requires either the suppression of positronium formation or the rapid destruction of orthopositronium on time scales less than its $\sim 10^{-7}$ sec annihilation lifetime. Orthopositronium can be broken up before annihilation if the density of the ambient medium exceeds $\sim 10^{15}$ e/cm$^3$ (Crannell et al. 1976), or if the radiation density above a photon energy of $\sim 6.8$ eV exceeds $\sim 10^3$ erg/cm$^3$ (Lingenfelter and Ramaty 1983). Orthopositronium annihilation can also be suppressed by the presence of either large ($> 1000$ Gauss) magnetic fields (Crannell et al. 1976), or most likely large amounts of dust (Zurek 1985).

The direct correlation between variations in the annihilation line flux and the continuum flux at higher energies strongly suggests (Ramaty and Lingenfelter 1987) that the variation in the 511 keV line intensity was caused by a change in the positron production rate at the source, and not by a change in the properties of the annihilation region, affecting the rate of annihilation, as has been suggested (Weber et al. 1986).

## 5.2 THE POSITRON SOURCE

The variable 511 keV line flux observed from the compact source during 1977 – 1979, which reached $\sim 10^{-3}$ photons/cm$^2$ sec, implies an annihilation radiation luminosity of $\sim 1{\times}10^{37}$ ergs/sec at the distance (8.5 kpc) of the Galactic Center. Without accompanying orthopositronium continuum emission, this corresponds to a positron annihilation rate, and in equilibrium a positron production rate of $\sim 5{\times}10^{42}$ positrons/sec.

The nature of this positron source is also strongly constrained by the observed variation of the 511 keV line intensity and the higher energy ($> 511$ keV) continuum. The decrease of a factor of three in the line intensity in six months clearly excludes any of the multiple, extended sources, such as cosmic rays, pulsars, supernovae, or primordial black holes, previously proposed. As noted above, the correlation between the line and higher energy continuum intensities also argues strongly against the possibility (Weber et al. 1986) that the compact-source positrons result from the decay of long-lived ($\sim 10^6$ yr) $^{26}$Al produced by thermonuclear burning in a single massive supernova explosion, since in such a case, the $> 511$ keV continuum emission would not be correlated with the annihilation line emission. Thus, the observations require a single, compact ($< 10^{18}$cm) source which is inherently variable on time scales of six months or less.

In principle, positrons can be produced in such a source either directly or indirectly by a number of processes:

$e^+$ decay of $\pi^+$ mesons produced in high energy nuclear interactions and matter-antimatter annihilation;

$e^+$ decay of radionuclei produced in low energy nuclear reactions;

$e^\pm$ pair production in electron-electron and electron-nucleus interactions;

$e^\pm$ pair production in photon-electron and photon-nucleus interactions;

$e^\pm$ pair production in photon-photon interactions;

$e^\pm$ pair production in interactions of both photons and electrons with intense magnetic fields.

But as we have previously shown (Lingenfelter and Ramaty 1982, 1983), in a review of the various possible positron production processes and the observational constraints on them, the observations of the accompanying continuum emission at energies > 511 keV set the strongest constraint on the positron production process, because the observations require a very high efficiency, such that about 5% of the total radiated energy > 511 keV goes into electron-positron annihilation radiation. We thus found that under the conditions that the positron production occurs on time scales comparable to that of the observed variation and in an isotropically emitting region, only photon-photon pair production by these > 511 keV photons can provide the required high efficiency. Moreover, the absolute luminosity of the annihilation line requires that the photon-photon collisions take place in a very compact source ($r < 5\times10^8$cm). Pair production in an intense radiation field around an accreting black hole of $< 10^3\ M_\odot$ appears to be a possible source. If the emission is not isotropic, the positrons could also result from pair production by small angle photon interactions in a beamed electromagnetic cascade, generated by a dynamo around a massive ($\sim 10^6\ M_\odot$) rotating black hole. But in such a case one should expect to see some variation in the much higher energy gamma ray emission and this has not been reported.

These conclusions result from the following arguments, in which we considered (Lingenfelter and Ramaty 1983) two geometries for the positron production region: a spherical volume in which $e^+$-$e^-$ pairs are produced by photons interacting isotropically and a beam in which the pairs are produced by photon interactions only at small angles.

The most efficient pair production occurs in isotropic interactions of photons at energies close to $m_ec^2$. The pair production rate $Q$ in a spherical source of radius $r$ may be approximated by

$$Q \sim n_\gamma^2 < \sigma c > 4\pi r^3/6,$$

where $< \sigma c >$ is the average pair production cross section times the velocity of light, equal to $\sim 3\times10^{-15}$ cm$^3$/sec for black body photons of temperature $\sim m_ec^2$, and $n_\gamma$ is the photon number density. Assuming that the source is optically thin, the photon density can also be related to the continuum luminosity at energies $\geq m_ec^2$ by

$$L \sim \epsilon n_\gamma c 4\pi r^2,$$

where $\epsilon$ is the average photon energy and $r/c$ is the photon residence time. Combining these two equations and setting $\epsilon \sim m_ec^2$, we see that for a given continuum luminosity the positron production rate depends only on the source size, such that the radius,

$$r \sim \frac{< \sigma c > L^2}{24\pi c^2 (m_ec^2)^2 Q} \sim 6.6\times10^{-26} L^2/Q(cm).$$

From the observed > 511 keV luminosity of $L \leq 2\times10^{38}$ erg/sec and a production rate $Q$ equal to the annihilation rate of $5\times10^{42}$ $e^+$/sec, the radius of the positron source must be $\leq 5\times10^8$ cm.

Pair production by isotropic photon-photon interactions thus requires an exceedingly compact source with a high luminosity. The most obvious candidate is a black hole. If this source is a black hole releasing gravitational energy of accreting matter close to its Schwarzschild radius, then it must have a mass $< 10^3\ M_\odot$, which is much smaller than the possible $10^6$ to $10^7\ M_\odot$ black holes that have been suggested (e.g. Lacy et al. 1980) at the Galactic Center. Such a small size is consistent, however, with arguments by Ozernoy (1979) that the Galactic Center cannot contain a black hole larger than about $10^2$ $M_\odot$, if tidal disruption of stars is the principal source of the accreting matter on which it grows.

The > 511 keV continuum photons needed to produce the pairs could themselves be produced in a hot accretion disk around the black hole (e.g. Eardley et al. 1978). A variable luminosity of as much as $2\times10^{38}$ erg/sec requires an accretion rate of as much as $3\times10^{-8}$ $M_\odot$/yr which would form a $\leq$ 300 $M_\odot$ hole in the age of the Galaxy. A major fraction of the $e^\pm$ pairs produced by photon-photon collisions above the disk could then escape from the source region before they annihilate, a constraint (Table 1) set by the absence of any measurable redshift in the energy of the annihilation line. Further calculations of such production have been made by McKinley (1986) and Carrigan and Katz (1987).

The escape of such positrons would also be aided by the fact that, as long as the compact source mass is < $10^3$ $M_\odot$, a luminosity of $\sim 2\times10^{38}$ erg/sec is greater than the Eddington luminosity for an electron-positron plasma, which is only $m_e/m_p$ of that for normal matter. Thus the radiation pressure on the electron-positron plasma exceeds the gravitational attraction and can help blow them out of the source.

We turn now to the alternative geometry of pair production by small angle photon interactions in a beam, which may be produced (Blandford 1979, Lovelace, McAuslan and Burns 1979) by dynamo action in a magnetic field accreting onto a black hole. Several variations on this possibility for producing positrons in the Galactic Center have been suggested (Blandford 1982, Burns 1983, Lingenfelter and Ramaty 1983). In addition, Kardashev et al. (1983) considered the relatively less efficient production by beam photons interacting with gas in a cloud. We showed (Lingenfelter and Ramaty 1983) that with a beam the constraint on the size of the production region could be greatly relaxed, but at the expense of a much higher beam luminosity in gamma rays of energy $\gg m_ec^2$.

The pair production rate $Q$ for small angle ($\theta \sim r_b/l$) photon interactions in a beam of radius $r_b$ and length $l$ may be approximated by

$$Q \sim n_\gamma^2 < \sigma v_\perp > \pi r_b^2 l/2,$$

where $v_\perp \sim (r_b/l)c$ is the mean transverse velocity of the interacting photons, and $n_\gamma$ is the density of those photons with energies greater than the small angle pair production threshold $E_{th} \sim (l/r_b)m_ec^2$. This density can be related to the beam luminosity of such photons by

$$L_b \sim (l/r_b)m_ec^2 n_\gamma c\pi r_b^2.$$

Combining these two equations, we see that the beam radius is

$$r_b \sim \frac{< \sigma c > L_b^2\theta^2}{2\pi c^2(m_ec^2)^2 Q} \sim 8 \times 10^{-25} L_b^2\theta^2/Q(cm).$$

Thus, for a pair production rate $Q$ of $5\times10^{42}$ $e^+$/sec, the beam radius could be as big as $\sim 10^{12}$ cm, or equal to the Schwarzchild radius of a $3\times10^6$ $M_\odot$ black hole, if the aspect ratio of the beam $\theta \sim 0.02$, or 1°, and the beam luminosity at photon energies greater than 25 MeV were as high as half the Galactic Center bolometric luminosity limit of $\sim 3.5\times10^{41}$ erg/sec (e.g. Lacy et al. 1980).

The resulting pairs would also have energies of $\sim$ 25 MeV, comparable to those of the photons which produced them. But they could be stopped and annihilate to give the observed narrow 511 keV line emission, if the beam hit a gas cloud. The bulk of the pair energy, amounting to $\sim 10^{40}$ erg/sec, would be dissipated in heating the gas which could in turn reradiate it isotropically as thermal radiation consistent with the constraints on the $\leq$ 30,000 K luminosity (Lacy et al. 1980). Since the radiation yield of $\sim$ 25 MeV electrons and positrons is $\leq 3\%$, their bremsstrahlung could also be consistent with the hard X-ray and gamma-ray luminosity limit of $\leq 2\times10^{38}$ erg/sec. But such a geometry would not directly account for the observed continuum flux $>$ 511 keV and it would require variations in the higher energy ($>$ 25 MeV) flux which have not been reported (Swanenburg et al. 1981).

## 6. The Nature of the Diffuse Galactic 511 keV Emission

Lastly we consider the origin of the diffuse annihilation radiation from the galactic disk. The SMM and other observations show that there is a diffuse galactic component of the 511 keV line emission with an intensity of $\sim 1.5\times10^{-3}$ photons/cm$^2$ sec rad of galactic longitude in the direction of the galactic center. This emission can account for all of the annihilation radiation observed from the direction of the Galactic Center after 1979 and much of that before that time. The high resolution HEAO-3 observations in the spring of 1980, which appear to be entirely of diffuse origin, also show a positronium continuum component with an intensity of $\sim 7\times10^{-3}$ photons/cm$^2$ sec rad, implying that nearly all of the diffuse positrons annihilate via positronium. As mentioned above, in a partially ionized gas, the fraction of positrons annihilating via positronium could be practically 1 (Bussard, Ramaty and Drachman 1979). Comparison of the measured flux as a function of detector field of view also shows that the intensity of the line emission varies with galactic longitude similar to that of the high energy ($>$ 70 MeV) gamma-ray emission, or the molecular (CO) gas. The observed fluxes thus require an average total galactic positron production rate of $\sim 3.6\times10^{43}$ positrons/sec, assuming steady state with 100% of the positrons annihilating via positronium.

Measurement of the diffuse annihilation radiation is of great importance to our understanding of galactic nucleosynthesis. For although there are a variety of sources of positrons in the galactic disk, we have shown (Ramaty and Lingenfelter 1979) that the dominant source should be positrons from the decay of radionuclei, resulting from explosive nucleosynthesis in supernovae. Recent estimates (Lingenfelter 1988) of the average rates of positron production from various possible galactic sources are summarized in Table 2.

As can be seen the most likely source of these diffuse interstellar positrons is $\beta^+$ decay of either $^{56}$Co (Clayton 1973, Ramaty and Lingenfelter 1979) or $^{44}$Sc (Woosley 1987) made by explosive nucleosynthesis in Type I supernovae. Because of the much greater mass and slower expansion velocity of the nebulae of Type II supernovae, the $^{56}$Co decay positrons produced there should nearly all annihilate before the nebulae become transparent with only a negligible fraction escaping. The relative importance of $^{56}$Co and $^{44}$Sc depends on the fraction $\epsilon$ of $^{56}$Co decay positrons that can escape into the interstellar medium from a Type I supernova. If the positron escape fraction $\epsilon$ is $> 0.8\%$, then $^{56}$Co decay is the dominant positron source. This escape fraction is very uncertain with theoretical estimates ranging as high as 10% (Colgate 1970). If $^{56}$Co is the dominant source, the observations imply that $1.5\% < \epsilon < 3.8\%$ for Type I supernova rates of one every 50 to 100 yrs. As we previously pointed out (Lingenfelter and Ramaty 1979), escaping positrons from $^{56}$Co decay could be accelerated in supernovae to produce a detectable component in the cosmic ray electrons and here we suggest that the acceleration of the positrons in the supernova ejecta could also aid in their escape.

**Table 2. Average Galactic Positron Production Rates Over Positron Lifetimes of $\sim 10^5$ Years in ISM**

| POSITRON SOURCE | PRODUCTION PROCESS | AVERAGE RATE $10^{43}$ $e^+$/sec | REF. |
|---|---|---|---|
| Supernovae Type I | $^{56}Co(\beta^+)^{56}Fe$ 19% | $70\epsilon/\tau_{100}$ | (1) |
| Supernovae Type I | $^{44}Sc(\beta^+)^{44}Ca$ 95% | $0.6/\tau_{100}$ | (2) |
| SN, Novae, Wolf-Rayet | $^{26}Al(\beta^+)^{26}Mg$ 82% | $0.35 \pm 0.07$ | (3) |
| SN, Novae, Wolf-Rayet | $^{22}Na(\beta^+)^{22}Ne$ 91% | $<0.7$ | (4) |
| Cosmic Rays in ISM | $pp \rightarrow \pi^+ \ldots$ | $<0.1$ | (5) |
| Gamma-Ray Bursts | $\gamma\gamma \rightarrow e^+e^-$ | $<0.3$ | (6) |
| Pulsars | $e^+e^-$ Cascade | $<0.1$ | (7) |
| REQD. GALACTIC PRODUCTION | | $\sim 3.6$ | |

**References:** (1) Assuming a rate of 1 SNI per $\tau = 100$yr with $^{56}$Ni mass of 0.5 $M_\odot$ and $e^+$ escape fraction $\epsilon$. (2) Assuming all $^{44}$Ca from $^{44}$Sc and local abundance ratio of $^{44}Ca/^{56}Fe$ of $1.6 \times 10^{-3}$ (Cameron 1982). (3) From observed 1.809 MeV line flux of $(4.3 \pm 0.8) \times 10^{-4}$ photons/cm$^2$sec rad (Mahoney et al. 1984). (4) From observed (Mahoney et al. 1982) limit on 1.275 MeV flux requiring $^{22}Na/^{26}Al < 1.7$ (Higdon and Fowler 1987). (5) From observed flux of $> 100$ MeV limiting $\pi^o \rightarrow 2\gamma$ (Harding and Stecker 1981). (6) From gamma ray burst model calculations (Lingenfelter and Hueter 1984). (7) From pulsar model calculations (Sturrock 1971).

Once they escape into the interstellar medium, the positrons should have a mean life against annihilation of about $10^5$ yrs (see Bussard, Ramaty and Drachman 1979), so that positrons from over a thousand supernovae should combine to produce the steady observed disk component of annihilation radiation.

Although diffuse galactic gamma ray line emission at 1.809 MeV has also been observed (Mahoney et al. 1984, Share et al. 1985) from decay of the long lived positron emitting radioisotope $^{26}$Al, as can be seen, the positrons from such decay can account for only $10\pm2\%$ of the observed diffuse annihilation radiation. The contribution of $^{22}$Na is $< 19\%$, probably much less, and the contributions of other suggested sources is even less.

## 7. Conclusions

In conclusion we have found that:

• In the Galactic Center or its vicinity there is a variable compact source of 511 keV line emission and $>$ 511 keV continuum. Evidence for this source is in the flux variations observed with the same detectors at different times. This source was active during the period from about 1977 through 1979. There is no evidence of orthopositronium continuum emission from this source.

• The location of the compact source is not known precisely, the only direct observation places it within 4° of the Galactic Center. The correlation of the 511 keV line and $>$ 511 keV continuum fluxes strongly suggests that the observed line flux variability is due to a variable positron source and not to variations in the properties of the annihilation site. The high ratio of the line-to-continuum luminosities implies positron production by photon-photon interactions and a source size of $\leq 5\times10^8$ cm for an isotropically emitting object, suggesting a black hole of mass $< 10^3$ $M_\odot$. Such an object need not reside at the Galactic Center.

• There is also steady, diffuse 511 keV line and orthopositronium continuum emission from the galactic disk that is unrelated to the Galactic Center. Evidence for this emission comes from the comparison of observations with gamma ray spectrometers of narrow and broad fields of view. This diffuse source has shown no temporal variations.

• The diffuse positron annihilation radiation from the galactic disk results from the annihilation of positrons, which most likely escape into the interstellar medium from supernovae where they were produced primarily in the decay of $^{56}$Co to $^{56}$Fe. The lifetime of these positrons in the interstellar medium is expected to be $\sim 10^5$ yr or more.

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## REFERENCES

Albernhe, F., et al. 1981, *Astron. Astrophys.*, **94**, 214.

Blandford, R. D. 1979, in *Active Galactic Nuclei,* (London: Cambridge Univ.) p. 241.

———. 1982, in *The Galactic Center,* ed. G. R. Riegler and R. D. Blandford (New York: Am. Inst. Phys.) p. 177.

Brown, B. L., and Leventhal, M. 1987, *Astrophys. J.,* **319**, 637.

Brown, B. L., Leventhal, M., and Mills, A. P., Jr. 1986, *Phys. Rev.,* **A33**, 2281.

Burns, M. L. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. L. Burns, A. K. Harding, and R. Ramaty, (New York, Am. Inst. Phys.) p. 281.

Bussard, R. W., Ramaty, R., and Drachman, R. J. 1979, *Astrophys. J.,* **228**, 928.

Cameron, A. G. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge Univ.) p. 23.

Carrigan, B. J., and Katz, J. I. 1987, *Astrophys. J.,* **323**, 557.

Clayton, D. D. 1973, *Nature Phys. Sci.,* **244**, 137.

Colgate, S. A. 1970, *Astrophys. Space Sci.,* **8**, 457.

Cook, W. R., et al., (This volume).

Crannell, C. J., et al. 1976, *Astrophys. J.,* **210**, 582.

Dunphy, P. P., Chupp, E. L., and Forrest, D. J. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. L. Burns, A. K. Harding, and R. Ramaty, (New York, Am. Inst. Phys.) p. 237.

Eardley, D. M., et al. 1978, *Astrophys. J.,* **224**, 53.

Gardner, B. M., et al. 1982, in *The Galactic Center,* ed. G. R. Riegler and R. D. Blandford (New York: Am. Inst. Phys.) p. 144.

Harding, A. K., and Stecker, F. W. 1981, *Nature,* **290**, 316.

Haymes, R. C., et al., 1975, *Astrophys. J.,* **201**, 593.

Higdon, J. C., and Fowler, W. A. 1987, *Astrophys. J.,* **317**, 710.

Johnson, W. N., Harnden, F. R., and Haymes, R. C. 1972, *Astrophys. J.,* **172**, L1.

Johnson, W. N., and Haymes, R. C. 1973, *Astrophys. J.,* **184**, 103.

Kardeshev, N. S., et al. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. L. Burns, A. K. Harding, and R. Ramaty, (New York, Am. Inst. Phys.) p. 253.

Knight, F. K., et al. 1985, *19th Internat. Cosmic Ray Conf. Papers,* **1**, 217.

Lacy, J. H., et al. 1980, *Astrophys. J.,* **241**, 132.

Leventhal, M. 1973, *Astrophys. J.,* **183**, L147.

Leventhal, M., et al. 1980, *Astrophys. J.,* **240**, 338

———. 1982, *Astrophys. J.,* **260**, L1.

———. 1986, *Astrophys. J.,* **302**, 459.

Leventhal, M., MacCallum, C. J., and Stang, P. D. 1978, *Astrophys. J.,* **225**, L11.

Levine, A. M., et al. 1984, *Astrophys. J. Supp.,* **54**, 581.

Lingenfelter, R. E. 1988, *20th Internat. Cosmic Ray Conf. Papers,* **8**, 7.

Lingenfelter, R. E., and Hueter, G. J. 1984, in *High Energy Transients in Astrophysics,* ed. S. E. Woosley (New York: Am. Inst. Phys.) p. 558.

Lingenfelter, R. E., and Ramaty, R., 1979, *16th Internat. Cosmic Ray Conf. Papers,* **1**, 501.

———. 1982, in *The Galactic Center,* ed. G. R. Riegler and R. D. Blandford (New York: Am. Inst. Phys.) p. 148.

———. 1983, in *Positron-Electron Pairs in Astrophysics*, ed. M. L. Burns, A. K. Harding, and R. Ramaty, (New York: Am. Inst. Phys.) p. 267.

———. 1985, *19th Internat. Cosmic Ray Conf. Papers,* **9**, 19.

Lovelace, R. V. E., McAuslan, J., and Burns, M. L. 1979, in *Particle Acceleration Mechanisms in Astrophysics,* ed. J. Arons, C. Max and C. McKee, (New York: Am. Inst. Phys.) p. 399.

Mahoney, W. A. 1988, in *Nuclear Spectroscopy of Astrophysical Sources,* ed. N. Gehrels and G. H. Share, (New York: Am. Inst. Phys.) p. 149.

Mahoney, W. A., et al. 1982, *Astrophys. J.,* **262**, 742.

———. 1984, *Astrophys. J.,* **286**, 578.

Matteson, J. L. 1982, in *The Galactic Center,* ed. G. R. Riegler and R. D. Blandford (New York: Am. Inst. Phys.) p. 109.

Mayer-Hasselwander, H. A., et al. 1980, *Ann. N. Y. Acad. Sci.,* **336,** 211.

McKinley, J. M. 1986, *Proc. Third Internat. Workshop on Positron Gas Scattering,* (Singapore: World Scientific), p. 152.

Ozernoy, L. M. 1979, in *The Large-Scale Characteristics of the Galaxy,* ed. W. B. Burton, (Dordrecht: Reidel) p. 395.

Paciesas, W. S., et al. 1982, *Astrophys. J.,* **260**, L7.

Ramaty, R., and Lingenfelter, R. E., 1977, *Astrophys. J.,* **213**, L5.

———. 1979, *Nature,* **278**, 127.

———. 1981, *Phil. Trans. Roy. Soc. London,* **A 301**, 671.

———. 1982, *Ann. Rev. Nucl. Part. Sci.,* **32**, 235.

———. 1987, in *The Galactic Center,* ed. D. Backer (New York: Am. Inst. Phys.) p. 51.

Riegler, G. R., et al. 1981, *Astrophys. J.,* **248**, L13.

———. 1985, *Astrophys. J.,* **294**, L13.

Schoenfelder, V., von Ballmoos, P., and Diehl, R. 1987, *20th Internat. Cosmic Ray Conf. Papers,* **1**, 109.

Share, G. H., et al. 1985, *Astrophys. J.,* **294**, L61.

———. 1988, *Astrophys. J.,* **326**, 717.

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

Sturrock, P. A. 1971, *Astrophys. J.,* **164**, 529.

Swanenburg, B. N., et al. 1981, *Astrophys. J.,* **243**, L69.

Weber, W. R., et al. 1986, *Nature,* **323**, 692.

Woosley, S. E. 1987, private communication.

Zurek, W. H. 1985, *Astrophys. J.,* **289**, 603.