POSITRON-ELECTRON ANNIHILATION RADIATION FROM THE GALACTIC CENTER

R. Ramaty, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.
R. E. Lingenfelter, Center for Astrophysics and Space Sciences, University of California, La Jolla, CA 92093, U.S.A.

ABSTRACT

We discuss observations of the intense, time variable and very narrow 0.511 MeV positron-electron annihilation line from the Galactic Center, and the implications of these and other observations on the source of the positrons and their annihilation site.

INTRODUCTION

We have recently reviewed (Lingenfelter and Ramaty 1982) the origin of the 0.511 MeV line observed from the Galactic Center and concluded that the most probable mechanism for producing this radiation is photon-photon pair production near a $\lesssim 500\ M_\odot$ black hole at the center of our galaxy. Here we present a brief summary of the evidence and arguments leading to this conclusion. We start by reviewing the observations and then proceed to discuss their implications on the annihilation site and on the positron source.

THE OBSERVATIONS

Intense positron annihilation radiation at 0.511 MeV has been observed from the direction of the Galactic Center for over a decade. This emission was first seen in a series of balloon observations with low-resolution NaI detectors starting in 1970 (Johnson, Harnden and Haymes 1972, Johnson and Haymes 1973, Haymes et al. 1975). But it was not until 1977 that the annihilation line energy of 0.511 MeV was clearly identified with high-resolution Ge detectors flown by Leventhal, MacCallum and Stang (1978). The latter observation also revealed that the line is very narrow (FWHM $\lesssim$ 3.2 keV) and that the continuum below 0.511 MeV could contain a significant contribution from positronium annihilation.

The existence of this very narrow line was confirmed by observations (Riegler et al. 1981) with Ge detectors on HEAO-3.

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These observations set an even more stringent limit on the line width (FWHM < 2.5 keV), determined the line center energy as 510.90 ± 0.25 keV, provided new information on the spatial extent of the emission region and showed that the line intensity varies in time. The HEAO-3 observations showed that the line emitting region is smaller than the angular resolution of the detector (35°FWHM) and that the direction of the source coincides with that of the Galactic Center, within the observational uncetainty of ± 4°. These observations also showed that the 0.511 MeV line intensity decreased by a factor of three in six months, from $(1.85 \pm .21) \times 10^{-3}$ photons/cm^2 sec in the fall of 1979 to $(0.65 \pm .27) \times 10^{-3}$ photons/cm^2 sec in the spring of 1980. Variability of this intensity has been confirmed by balloon-borne Ge detector observations (Leventhal et al. 1982, Paciesas et al. 1982). Furthermore, NaI detector observations in the fall of 1977 (Gardner et al. 1982) could indicate a variation on a time scale as short as 10 days.

Observations of continuum emission in the hard X-ray and gamma-ray bands have recently been reviewed by Matteson (1982). The hard X-ray emission is also time variable and is weakly correlated with the variability of the 0.511 MeV line (e.g. Paciesas et al. 1982). These observations set an upper bound of 2×10^{38} erg/sec on the Galactic Center continuum luminosity at photon energies $> m_e c^2$, since only part of this emission may come from the same source as the annihilation radiation.

THE ANNIHILATION REGION

The nature of the positron annihilation region is constrained by the intensity variations, the line width and the line center energy. The size of the region should not exceed about 10^{18} cm, the distance traveled by relativistic positrons in 1/2 year, and the density of the gas in which the positrons annihilate should be larger than 10^5 cm^{-3}, the minimum density required to slow them down in 1/2 year.

The observed line width requires (Bussard, Ramaty and Drachman 1979) that this gas be at least partially ionized ($n_e > 0.1n$). If the gas were neutral, the line width would be larger than observed because it would be Doppler broadened, not by the thermal motion of the gas, but by the velocity of energetic positrons forming positronium in flight by charge exchange with neutral hydrogen. In a partially ionized gas, however, positrons lose energy to the plasma fast enough that the positrons thermalize before they annihilate or form positronium. The line width thus reflects the temperature of the medium, so that the observations require a temperature $\lesssim 5 \times 10^4$ K. The line width further limits any velocities of rotation, expansion or random motion to <700 km/sec, while the line center energy implies a bulk velocity along the line of sight -90 km/sec $<V<$ $+200$ km/sec and a gravitational redshift $Z<7 \times 10^{-4}$.

The above constraints are summarized in Table 1.

Table 1

Constraints on the e^+-e^- Annihilation Site at the Galactic Center

Physical Parameter	Constraint	Observation
Size	$<10^{18}$cm	variability
Gas density	$>10^5 cm^{-3}$	variability
Ionization state	$n_e/n>0.1$	line width
Temperature	$<5x10^4$K	line width
Rotation, expansion or random motion	<700km/sec	line width
Bulk motion along line of sight	-90km/sec<V<200km/sec	line center energy
Gravitational redshift	$Z<7x10^{-4}$	line center energy

As first pointed by Ramaty and Lingenfelter (1981), the most likely annihilation sites that satisfy these constraints are the warm clouds (Lacy et al. 1980) and other compact IR sources (Lo et al. 1981) observed within the central parsec of the galaxy.

THE POSITRON SOURCE

The nature of the positron source is also strongly constrained by the observed variation of the 0.511 MeV intensity and by observations at other wavelengths. 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 (Sturrock and Baker 1979), supernovae (Ramaty and Lingenfelter 1979), or primordial black holes (Okeke and Rees 1980), previously proposed. Instead, it essentially requires a single, compact ($<10^{18}$cm) source which is apparently located either at or close to the Galactic Center and which is inherently variable on time scales of six months or less.

The observed 0.511 MeV line intensity of ~ 2 x 10^{-3} photons/cm^2 sec requires at the distance of the Galactic Center (~10 kpc) a positron annihilation rate of ~4 x 10^{43} e^+/sec, if 90% of the positrons annihilate via positronium. This rate corresponds to a minimum luminosity of ~ 6 x 10^{37} erg/sec in annihilation radiation including both line and three-photon continuum. With such a luminosity, the Galactic Center is the most luminous gamma-ray source in the galaxy. The uniqueness of this source makes it unlikely that it results from the chance occurence of the youngest supernova or pulsar along the the line of sight to the center of the galaxy.

The strongest constraints on the various positron production processes are set (Lingenfelter and Ramaty 1982) by observations of continuum emission at energies $\gtrsim m_ec^2$ from the direction of the Galactic Center (e.g. Matteson 1982). When compared with the annihilation radiation luminosity, the continuum gamma ray luminosity implies a very efficient positron production process, one in which

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more than 30% of the total radiated energy $>m_ec^2$ goes into electron-positron pairs. Under the conditions of positron production on time scales comparable to that of the observed variation and in an essentially optically thin region which emits isotropically, only photon-photon pair production among ~ MeV photons can provide the required high efficiency.

The most efficient pair production occurs at photon energies close to m_ec^2. The pair production rate Q in a spherical source of diameter d may be approximated by $Q \sim \frac{1}{2} n_\gamma^2 \langle\sigma c\rangle d^3$, where $\langle\sigma c\rangle$ is the average pair production cross section times the velocity of light (equal to ~ 3×10^{-15} cm^3/sec for black body photons of temperature ~ m_ec^2, Weaver 1976) and n_γ is the photon number density. Assuming that the source is optically thin, this density can be related to L, the continuum luminosity $\geq m_ec^2$, by $L \sim m_ec^2 n_\gamma c\pi d^2$. Thus, for a given L, the positron production rate depends only on the size, such that $d \sim 3 \times 10^{-25}\ L^2/Q$ in cm. For the observed limiting luminosity $L \lesssim 2 \times 10^{38}$ erg/sec and annihilation rate $Q \simeq 4 \times 10^{43}\ e^+$/sec, the diameter of the positron source must be $\leq 3 \times 10^8$ cm.

Pair production in photon-photon collisions thus requires an exceedingly compact source. If this source is a blackhole releasing energy by accretion close to its Schwarzschild radius, then it must have a mass < 500 $M_\odot$ which is much smaller than the 10^6 to 10^7 $M_\odot$ blackholes that have been suggested (Lynden-Bell and Rees 1971, Lacy et al. 1980) at the Galactic Center. Yet such a small size would be consistent with arguments by Ozernoy (1979) that the Galactic Center cannot contain a blackhole 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 photons which produce the pairs could themselves be due to thermal bremsstrahlung of hot accreted matter (e.g. Eardley et al. 1978). The accretion rate necessary to produce a luminosity of 2×10^{38} erg/sec is ~ $10^{-8} M_\odot$/year, which could form a 100 $M_\odot$ hole in the age of the galaxy. The accreting matter density close to the hole (<3×10^8 cm) necessary to produce this luminosity by self Comptonized thermal bremmstrahlung (McKinley and Ramaty 1983) in a source of optical depth of order unity is ~ 10^{17}cm^{-3}. This density is sufficiently low to allow a major fraction of the positrons to escape from their source region before they annihilate, a constraint (Table 1) set by the absence of any measurable redshift in the energy of the annihilation line.

SUMMARY

The observed time variations and line width of the e^+-e^- annihilation radiation from the Galactic Center require that the positrons be essentially produced by a single source and that they annihilate in an ambient gas of density $>10^5$cm^{-3}, ionization fraction >10%, temperature $<5 \times 10^4$K, and confined to a region of size $<10^{18}$

cm. Such conditions may exist in warm clouds and other IR sources within the central parsec of the galaxy.

The limits on the accompanying continuum emission at energies $>m_ec^2$ set strong constraints on the positron production process, requiring an exceedingly high efficiency, such that almost half of the total radiated energy $>m_ec^2$ goes into e^+-e^- pairs. The most likely mechanism appears to be pair production in photon-photon collisions in the close vicinity of a <500 M_θ blackhole. The absence of any measurable redshift in the line center energy requires that a large fraction of the positrons escape from the central source and annihilate at great distances ($>10^3$ Schwarzschild radii) from the hole.

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REFERENCES

Bussard, R. W., Ramaty, R. and Drachman, R. J.: 1979, Ap. J. 228, 928.
Eardley, D. M. et al.: 1978, Ap. J. 224, 53.
Gardner, B. M. et al.: 1982, The Galactic Center (AIP: New York), p. 144.
Haymes, R. C. et al.: 1975, Ap. J. 201, 593.
Johnson, W. N., Harden, F. R. and Haymes, R. C.: 1972, Ap. J. 172, L1.
Johnson, W. N. and Haymes, R. C.: 1973, Ap. J. 184, 103.
Lacy, J. H. et al.: 1980, Ap. J. 241, 132.
Leventhal, M. et al.: 1982, Ap. J. 260, L1.
Leventhal, M., MacCallum, C. J. and Stang. P. D.: 1978, Ap. J. 225, L11.
Lingenfelter, R. E. and Ramaty, R.: 1982, The Galactic Center (AIP: New York), p. 148.
Lo, K. Y. et al.: 1981, Ap. J., 249, 504.
Lynden-Bell, D. and Rees, M. J.: 1971, M.N.R.A.S., 152, 461.
Matteson, J. L.: 1982, The Galactic Center (AIP: New York), p. 109.
McKinley, J. M. and Ramaty R.: 1983, Bull. Amer. Astron. Soc. (in press).
Okeke, P. N. and Rees, M. J.: 1980, Astron. Astrophys. 81, 263.
Ozernoy, L. M.: 1979, Large Scale Characteristics of the Galaxy (Reidel: Dordrecht), p. 395.
Paciesas, W. S. et al.: 1982, Ap. J. 260, L7.
Ramaty, R. and Lingenfelter, R. E.: 1979, Nature, 278, 127.
Ramaty, R. and Lingenfelter, R. E.: 1981, Phil. Trans. R. Soc. Lond., A301, 671.
Riegler, G. R. et al.: 1981, Ap. J. 248, L13.
Sturrock, P. A. and Baker, K. B.: 1979, Ap. J. 234, 612.
Weaver, T. A.: 1976, Phys. Rev., 13A, 1563.