Primary Cosmic Ray Positrons and Galactic Annihilation Radiation

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ABSTRACT

The possibility of a primary positron component of the cosmic rays is suggested by the observation of intense positron annihilation radiation from the direction of the Galactic Center.

1. Introduction

The observation (1) of positron annihilation radiation at 0.511 MeV from the direction of the Galactic Center, forces a reexamination of the idea that the observed cosmic ray positrons are entirely of secondary origin, resulting from the decay of π^+ mesons produced in cosmic ray nucleonic interactions. Annihilation of positrons from π^+ decay cannot be the source of the observed 0.511 MeV emission because such an origin would require a galactic high energy (> 100 MeV) gamma ray luminosity from π° decay nearly two orders of magnitude greater than is observed. Clearly a much stronger additional source of positrons is required. Two possible sources of such positrons - decay of radionuclei (e.g. Co^{56} and Na^{22}) synthesized in supernova explosions and pair production in pulsar magnetospheres - produce relativistic ($\sim$1 MeV) positrons at what may be the acceleration sites of primary cosmic rays. If so, some fraction of these positrons could also be accelerated to cosmic ray energies by the same mechanism and at the same time that cosmic ray electrons and nucleons are accelerated. Observational evidence of the existence of primary positrons in the cosmic rays is discussed.

2. Annihilation Radiation from the Galactic Center

The Galactic Center annihilation radiation at 0.511 MeV is the best observed (1,2) celestial gamma ray line. The observed (1) line at 510.7 ± 0.5 keV has an intensity of 1.2×10^{-3} photons/cm^{2}sec and a full width at half maximum (FWHM) of less than 3.2 keV. This observation was made in 1977 with a balloon-borne high purity Ge detector of opening angle 15°, centered on the Galactic Center. The line energy clearly identifies it as positron annihilation radiation; there is also some evidence for the three-photon continuum from triplet positronium annihilation, implying $\sim$90% annihilation via positronium. This fraction is consistent with positron annihilation in a low density ($<10^{15}$cm^{-3}) and low temperature ($<10^6$K) medium (3,4), and implies about 0.6 photons in the 0.511 MeV line per positron. The 3.2 keV upper limit on the width of the 0.511 MeV line suggests (5) that the bulk of the positrons annihilate in an ionized medium ($n_e/n_H \gtrsim 0.05$), since in cold interstellar clouds, where the bulk of the positronium is formed before the positrons thermalize, the line width ($\sim$5 keV) would exceed the observed upper limit. Possible annihilation regions, which satisfy these conditions, are supernova remnants, HII regions at the Galactic Center, and the warm ionized component of the interstellar medium. The angular size of the emission region is not yet known, so the observed emission may come from just a portion of a broad region of the galactic disk extending well beyond the 15° opening angle of the detector, or it may all come from a single intense source much smaller than 15°. Further observations are clearly needed to resolve this question.

3. Possible Sources of Positrons

Taking an average distance of 10 kpc for the source of the annihilation radiation, the observed intensity of 1.2 x 10^{-3} photons/cm^2 sec implies an average positron production rate of ∿ 2 x 10^{43} positrons/sec. We shall consider a variety of possible sources of these positrons.

3.1 Cosmic Ray Interactions

Perhaps the best defined (6,7) source of positrons is the decay of π^+ mesons produced in high energy (≳ 1 GeV) cosmic ray interactions in the interstellar medium. Since π^o mesons, which decay by high energy gamma ray emissions, are also produced in these interactions, the measured flux of high energy (>100 MeV) gamma rays together with the measured π^+ and π^o production cross sections sets an upper limit on π^+ production. The observed (8) high energy gamma ray flux of ∿3 x 10^{-5} photons/cm^2sec from a 15° cone centered on the Galactic Center implies that not more than about 2% of the observed 0.511 MeV line can be from the annihilation of positrons resulting from π^+ decay.
Lower energy (< 100 MeV) cosmic rays also produce positrons through nuclear interactions which produce positron emitting radionuclei, such as ^{11}C, ^{13}N, ^{14}O and ^{15}O, or excite nuclear levels, such as that at 6.052 MeV in ^{16}O, which decay by electron-positron pair emission. The interstellar density of low energy cosmic rays is not known because solar modulation excludes the bulk of these particles from the inner solar system. But the maximum gamma ray line emission expected from these cosmic rays has been calculated (9) assuming a local interstellar density of 1 eV/cm^3, and substantial gradients along the line of sight towards the galactic center in both the cosmic ray energy density and heavy element abundances. If the cosmic ray intensity were increased, X-ray line emission at ∿6.8 keV due to charge exchange of fast Fe ions with interstellar matter would exceed the observational upper limit on this line, and if the heavy element abundances along the line of sight were increased, the absorption of X-rays would be larger than observed. The expected 0.511 MeV line intensity from low energy cosmic rays is also about 2% of that observed from the galactic center. Thus some other stronger source of positrons is clearly required.

3.2 Discrete Sources

Supernovae, pulsars and accreting blackholes could all be strong sources of positrons. But supernovae alone seem to be capable of producing all of the positrons required to account for the observed annihilation radiation (10). These positrons result from decay of relatively long-lived positron-emitting radioisotopes produced by nucleosynthesis during the explosive ejection of matter in supernova explosions. The principal positron producing decay chains are $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, yielding ∿ 0.2 positrons per ^{56}Co decay, and $^{22}Ne \rightarrow {}^{22}Ne$ with ∿ 0.9 positrons per decay. The ^{56}Co decay also produces gamma ray line emission at 0.847 and 1.238 MeV and ^{22}Na decay is accompanied by 1.275 MeV line emission.

Assuming (10) that all of the interstellar ^{56}Fe and ∿0.5% of the ^{22}Ne are produced explosively via these decay chains; the rate of positron production from ^{22}Na decay should be only $\sim 2 \times 10^{-2}$ of that from the Ni-Co-Fe decay.

Although nucleosynthesis takes place in dense regions which are opaque to gamma rays, the expanding envelope can become transparent if there is sufficient delay between the synthesis of the radioisotopes and the emission of the photons on their decay. Even if the lifetime of ^{56}Co is not long enough for the supernova to become transparent to its decay lines, a significant fraction of the positrons from ^{56}Co may escape from the supernova (11) and annihilate in regions which are transparent to the gamma rays. Since the slowing down and annihilation times of the positrons can be longer than the interval between supernova explosions, this could lead to an essentially steady galactic emission at 0.511 MeV.

It has been estimated (11) that about 0.1 of the positrons from ^{56}Co decay could escape from the supernova. This escape fraction would make ^{56}Co the dominant positron source for processes of nucleosynthesis. The production of $\sim 2 \times 10^{43}$ positrons/sec in the galaxy, as indicated by the 0.511 MeV line observation (1), would imply a present rate of nucleosynthesis of $\sim 10^{45}$ iron nuclei/sec. This is about 10% of the average rate of nucleosynthesis over the age of the galaxy, and is consistent with current models (12) of galactic evolution. The fraction of escaping positrons from supernovae is very uncertain, however, and requires further theoretical study. If the escape fraction for ^{56}Co were much lower than 0.1, ^{22}Na decay could become the dominant positron source, although this yield (13) is very uncertain as well. Novae may also produce ^{22}Na with a yield (14) of about 10^{48} nuclei per nova explosion, but the observed 0.511 MeV line emission would require about 600 novae per year which is an order of magnitude higher than current estimates.

One test of the explosive nucleosynthetic origin of the positrons would be the detection of the associated deexcitation gamma ray lines. A good prospect is the 1.809 MeV line from ^{26}Al decay (10). Because of the long lifetime of this isotope, the 1.809 MeV line should be observed as steady galactic emission with an intensity ∿2% of that of the 0.511 MeV line; the long half-life of the ^{26}Al also implies a very narrow width (∿3 keV) for the 1.809 MeV line.

Pulsars may also produce (15) positrons by pair production in their magnetospheres. But observations (16,17) of the Crab Nebula have so far not detected line emission at 0.511 MeV from this object. Although a line at 0.400 MeV, attributed to gravitationally redshifted 0.511 MeV emission, was detected (17) from the general direction of the Crab, this line was not seen (16) in an earlier flight which viewed the same region. It has been suggested (18) that the 0.400 MeV line was from a transient source other than the Crab.

Lastly, accretion around compact objects could also be a source of positrons. Nuclear interactions in a hot ($1 \text{ MeV} < T < 100 \text{ MeV}$) accreting gas could produce positrons without violating the constraints set by the X-ray observations. The resulting positron production, however, should be accompanied by strong, broad line emission from nuclear deexcitation, in particular the 4.44 MeV line from ^{12}C. This line was reported (2) in 1974 from the direction of the Galactic Center, but it was not seen in the recent HEAO-1 observations (19). If the 0.511 MeV emission comes from positrons produced in a single discrete source at the Galactic Center, such as a massive, accreting black hole (18) then such time variations in the prompt 4.44 MeV deexcitation line emission might be expected. But if the 0.511 MeV emission comes from positrons produced in a number of accretion sources so that the production is more nearly constant, then the HEAO-1 upper limit on the 4.44 MeV line intensity would require that not more than about 20% of the observed 0.511 MeV line results from positrons produced in such sources.

4. Primary Cosmic Ray Positrons

The observed 0.511 MeV emission requires a positron production rate nearly two orders of magnitude greater than the production rate of secondary cosmic ray positrons from decay of π^+ mesons produced in cosmic ray interactions. Since the most likely sources of these positrons, supernovae and pulsars, are both possible sources of the primary cosmic rays, it is obvious that if only a small fraction (∿1%) of these positrons were accelerated along with the cosmic ray nucleons and electrons to energies >100 MeV, these primary positrons could be comparable in intensity to the secondary positrons from π^+ decay.

Primary cosmic ray positron production in supernovae from decay of the ^{56}Ni-^{56}Co-^{56}Fe chain was first studied (11,20) as a possible source of intense low energy cosmic ray positrons tentatively reported (21) at 0.5 to 2 MeV. On subsequent analysis, however, this measurement proved to be only an upper limit and no further measurements of the low energy cosmic ray positron flux have yet been attempted. But the need for a strong positron source to explain the observed 0.511 MeV emission again makes Ni-Co-Fe chain positrons an attractive source. Furthermore if Fermi acceleration by turbulent motions in the supernova remnants (22) is the source of cosmic rays, some fraction of the Ni-Co-Fe and Na-Ne chains positrons should also be accelerated to higher energies. In such acceleration we would expect the $e^+/(e^+ + e^-)$ ratio to be independent of electron energy and to correspond to the ratio of positrons to electrons at the injection energy for acceleration.

Acceleration of positrons from pair production in pulsar magnetospheres (15,23) can also be a source of primary cosmic ray positrons. Recent calculations (23) suggest that pulsars may produce positrons of energies up to 3×10^3 GeV with relatively few electrons.

Such models of positron acceleration in supernovae and pulsars are not yet quantitative enough to place significant constraints on the expected flux of primary cosmic ray positrons, so that an estimate of the importance of such sources must be based on other observational evidence.

Since the observed (24) cosmic ray $e^+/(e^+ + e^-)$ ratio at energies of 0.1 to 1 GeV is significantly less than the ratio of ∿0.75 expected (7) for secondaries from $\pi^\pm$ decay, a primary electron component is also required. An upper limit on the $e^+/(e^+ + e^-)$ ratio in such primary electrons can be set from the minimum observed ratio. For if the primary ratio is independent of energy, then it cannot exceed the minimum observed (24) ratio of ∿0.05 at several GeV. This limit does not seem consistent with the model (23) of pulsar production and acceleration of positrons mentioned above.

More specific estimates of both the $e^+/(e^+ + e^-)$ ratio and the spectral shape of the primaries can be made from the observed variation of the cosmic ray positron to electron ratio with energy and from the interstellar cosmic ray electron spectrum of about $E^{-1.54}$ around a GeV, inferred (25) from the non-thermal galactic radio emission. The energy spectrum below several GeV measured near the Earth has been modified by solar modulation, but the positron to electron ratio should not be affected. Assuming that the primary electrons have an interstellar spectrum of $E^{-\Gamma}$ and a constant $e^+/(e^+ + e^-)$ ratio, and adding such a flux to that expected (7) in the interstellar medium from secondaries, we find that the combined interstellar cosmic ray electron spectrum would fit the $E^{-1.54}$ inferred from galactic radio emission and the combined $e^+/(e^+ + e^-)$ ratio would fit the observed (24) range from about 0.25 at 0.1 GeV to about 0.1 at 1 GeV, if the primary $e^+/(e^+ + e^-) \simeq 0.04$ and the spectral index $\Gamma \simeq 1.4$.

Because of uncertainties in both the inferred interstellar spectrum and in the measurements of the positron to electron ratio as a function of energy, these estimated properties of the primary spectrum are not unique. In fact any primary $e^+/(e^+ + e^-)$ ratio from 0 to <0.05 would be consistent within the present uncertainties in the measurements.

A primary cosmic ray electron spectrum of $E^{-1.4}$ and $e^+/(e^+ + e^-) \approx 0.04$ is nonetheless representative of what might be expected. Moreover such a primary flux could also account for the observed 0.511 MeV line emission from the direction of the Galactic Center. The measured (26) gamma ray flux between 50 and 100 MeV, which is thought to be primarily from bremsstrahlung, places a limit on the combined flux of positrons and electrons along a line of sight through the Galactic Center. Thus if we assume that the primary cosmic ray electrons above some energy, E_{min}, have an interstellar spectrum $\alpha\ E^{-\Gamma}$ and a constant $e^+/(e^+ + e^-)$ ratio, then the ratio of annihilation radiation emissivity to bremsstrahlung emissivity is given by

$$\frac{q(0.511)}{q_b(50\text{-}100)} = \frac{a\left(\frac{e^+}{e^+ + e^-}\right)\left(\frac{dE}{dt}\right) E_{min}^{-\Gamma}}{K(50^{-\Gamma+1} - 100^{-\Gamma+1})(\Gamma-1)^{-2}}$$

where a = 0.65 is the number of annihilation photons per positron; dE/dt roughly equals 2.4×10^{-13} MeV/Hatom sec electron, and K = 1.05×10^{-15} photons/Hatom sec electron. Such primary electrons with $\Gamma \approx 1.4$ and $e^+/(e^+ + e^-) \approx 0.04$ could account for the observed ratio of 0.511 MeV to 50-100 MeV photon fluxes of $\sim$ 100 to 150 if $E_{min} \approx 0.3$ MeV. This minimum energy, roughly corresponding to the injection energy for acceleration, is quite consistent with acceleration of positrons produced by ^{56}Co or ^{22}Na decay, which yield average positron energies of $\sim$ 1 MeV

Although we have seen that such primary cosmic ray positron fluxes would not be inconsistent with observations, further measurements are clearly required to determine whether primary positrons do in fact make a significant contribution to the cosmic ray positron flux. Because the contribution of secondary positrons from π^+ decay is greatest at $\sim$ 100 MeV, the primary positron contribution should be relatively more important at higher and lower energies. Measurements of the cosmic ray positron flux below 100 MeV however have serious uncertainties due both to the locally produced positron background and to solar modulation. Thus, the existence of primary positrons could best be tested by further measurement of the positron spectrum above about 10 GeV where these uncertainties become negligible.

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