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POSITRON-ANNIHILATION RADIATION

AUTHOR(S): Stirling A. Colgate, T-6

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MASTER
Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

POSITRONS FROM SUPERNOVA AND THE ORIGIN OF THE GALACTIC CENTER POSITRON ANNIHILATION RADIATION

Stirling A. Colgate

Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

The emission of positrons from supernova ejecta is discussed in terms of the galactic-center annihilation radiation. The positrons from the radioactive sequences $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ are the most numerous source from supernova. Only type I supernova will allow a significant fraction to escape the expanding ejecta. For a neutron-star model of a type I SN a fraction 4×10^{-3} of the escaped positron is enough to create the observed several year fluctuation of the annihilation radiation. The likelihood of this model is discussed in terms of other astrophysical evidence as well as the type I SN light curve.

INTRODUCTION

It is now generally agreed that the origin of the energy that powers the entire light curve of type I SN¹⁻⁵ and possibly part of the late time light curve of type II SN⁶ is due to the radioactive sequence $^{56}\text{Ni} \xrightarrow{6.1 \text{ d}} ^{56}\text{Co} \xrightarrow{77 \text{ d}} ^{56}\text{Fe}$. The nuclear physics that leads to this unique isotope is the thermonuclear synthesis of alpha particle nuclei C, O, and Si. The isotope ^{56}Ni is the minimum in the packing fraction curve of alpha particle nuclei, or the end point of nuclear synthesis starting from lighter alpha particle nuclei. As a consequence, the preponderance of ^{56}Ni causes its decay energy to dominate the heating of ejected matter during most of the subsequent expansion. Without a persistent energy source, adiabatic cooling during expansion would lead to much cooler matter. In this decay chain, positrons are produced in the last decay

$^{56}\text{Co} \xrightarrow[20\% \beta^+]{77 \text{ d}} ^{56}\text{Fe}$. It is primarily these positrons that are candidates for the production of the annihilation radiation from the galactic center from a previous supernova event, although other radioactive species particularly $^{22}\text{Na} \xrightarrow[90\% \beta^+]{3.8 \text{ y}} ^{22}\text{Ne}$ could contribute,⁷ to the positron annihilation flux.

The problems with each of these radioactive sources for an explanation of the galactic center radiation are:

1. number of positrons at the source
2. escape from the source (matter thickness and magnetic field)
3. lack of other gamma rays
4. special annihilation conditions.

REQUIRED SOURCE SIZE

If the usual assumption is made that the annihilation gamma ray flux of 1 to 2×10^{-3} photons $\text{cm}^{-2} \text{s}^{-1}$ observed at the earth indeed comes from the galactic center, then the recent several year fluctuation^{7,8} of roughly 2×10^{-3} photons $\text{cm}^2 \text{s}^{-1}$ for a year at the distance of the galactic center requires a single source of 3×10^{50} positrons, or for example, $10^{-4} M_{\odot}$ of ^{56}Ni , or $10^{-5} M_{\odot}$ of ^{22}Na . The likely production of ^{22}Na per supernova is less than $10^{-6} M_{\odot}$ for type I⁹ and so it is not further considered here. This is a small mass of ^{56}Ni but isotope production, decay, and positron escape fraction significantly restrict the possibilities for even these small requirements. The escape fraction of ^{56}Ni positrons from supernova ejecta depend critically on the supernova model.

ESCAPE OF POSITRONS

Electrons or positrons lose energy by ionization in the medium. The spectrum of beta particles results in a distribution in range and hence an escape fraction dependent on thickness for a source medium such as supernova ejecta. In ref. 3 the effective range for the ^{56}Co beta particles and the escape fraction for various supernova models of the radial distribution of the source function were considered. Surprisingly, the range distribution to first order behaves like an exponential absorption similar to the exponential absorption of gamma rays, or a range of equivalent constant cross section. This result also applies whether or not a "combed" dipole magnetic field as would occur in the radial expansion of the electrically conducting ejecta is present. Hence the Monte Carlo deposition and escape calculations which were applied to determine the gamma ray heating and escape fraction can be carried over to the positron case with an effective range or absorption mean free path of $\lambda_+ = 0.1 \text{ g cm}^{-2}$. (This range assumed high atomic number matter, i.e., ^{56}Fe ionized no more than several times. Ionized hydrogen would result in approximately 1/10 this effective range.) The escape fraction can then be calculated using $(1 - D)$, where D is the deposition fraction of Table 1 of ref. 3. In essence, 50% escape occurs when $\tau \equiv \rho R / \lambda_+ = 1$, or when $\rho R = 0.1 \text{ g cm}^{-2}$. At early times when $\tau > 1$, the escape fraction is increasing rapidly as τ decreases. Later it approaches unity for $\tau \ll 1$. Hence if the time, t_1 , when $\tau = 1$ is large compared to the lifetime of the radioactive positron decay nucleus, t_+ , then the attenuation acts as a window opening near $\tau = 1$, or $M / [4\pi R^2 \lambda_+] = 1$. This model would apply to a type II SN where a large envelope of hydrogen blankets a small core of radioactive ^{56}Co . The number of positrons escaping through such a

- $(\rho R / \lambda_+)$

blanket is proportional to $e^{-\tau}$. The actual escape is more complicated than this, but the ratio, t_1/t_+ , gives some indication of the escape probability for various supernova models. Generally supernova all seem to have the same total kinetic energy of roughly 10^{51} ergs or less, independent of type as interpreted from an integration of supernova remnant emission,¹⁰. For a uniformly expanding mass M whose velocity is v at the outer radius R , then the kinetic

energy is $(3/5) M v^2/2$, so that the time t_1 to reach a thickness λ_+ becomes:

$$\begin{aligned} t_1 &= 5.4 \times 10^6 M (\lambda_+ E_{51})^{-1/2} \quad \text{s.} \\ &= 620 M (\lambda_+ E_{51})^{-1/2} \quad \text{d.} \end{aligned} \quad (1)$$

Here M is in solar masses λ_+ in 0.10 g cm^{-2} and E_{51} in 10^{51} ergs. Thus for a type II supernova where the ^{56}Ni would be a small central region surrounded by $10 M_\odot$ of expanding hydrogen and where $\lambda_+ \approx 0.01 \text{ g cm}^{-2}$, $t_1 = 2 \times 10^4$ days, or $t_1/t_+ = 177$ for $t_+ = 111$ days of ^{56}Co . The escape fraction is then a number far too small to reasonably account for the positrons of the galactic center even for a solar mass of ^{56}Ni . Thus positron escape from models of SN I is more likely.

Three models of SN I are considered:

1. A bare mass of ^{56}Ni , $1.41 M_\odot$, and $E_{51} = 1$ resulting from a thermonuclear explosion.
2. A sphere of $0.7 M_\odot$ of ^{56}Ni surrounded by $0.7 M_\odot$ of lighter elements again from a thermonuclear explosion $E_{51} \approx 1$.
3. A neutron star model for which $0.25 M_\odot$ of ^{56}Ni is surrounded by $0.25 M_\odot$ of lighter elements, (ref. 3) $E_{51} = 0.67$.

The bare ^{56}Ni mass allows significant escape from a surface layer λ_+ thick. However, such a model places too much iron into the interstellar medium,¹¹ does not have the lighter element mantle necessary to give the absorption spectra on top of a photosphere characteristic of SN I¹² and results in too high a peak luminosity to be consistent with $H_0 > 50$.⁵ Hence the second thermonuclear model is favored over the first. Here positron escape is more complicated due to details of the model, but in general positron escape is more attenuated than the bare source model because of the interior source and finite range of positrons. The positrons from models 2 and 3 will be roughly the same, but I prefer the third model of a neutron star because we have already calculated the positron escape fraction as $\approx 10\%$, ref. 3. In this case $0.025 M_\odot$ of ^{56}Ni would contribute to escaped positrons, and only a fraction 4×10^{-3} of these escaped positrons are needed to supply the galactic center source.

The reasons for considering the collapse to a neutron star for type I supernova are:

1. The high doppler velocity of the ejecta (1.5 to $2 \times 10^9 \text{ cm s}^{-1}$) and limited kinetic energy give better agreement with low ejected mass;¹³
2. The observation of binary neutron stars (pulsars and rapid pulsating x-ray sources) demands neutron star formation with a low mass of ejecta (less than the total mass, to remain bound) and

3. The exponential, late-time light decay of 56 day half life is explained only by the escape of positrons from a small mass of ejecta.
4. The peak luminosity of type I SN can be interpreted in terms of the Hubble constant and mass of ^{56}Ni ,⁵ as $H \approx 40 M_{\text{Ni}}^{-1/2}$, an uncomfortably small value for a white dwarf explosion of $1.4 M_{\odot}$ of ^{56}Ni .
5. The rate of iron production in the solar neighborhood as well as the galaxy is too large by 5 to 10 fold for $1.4 M_{\odot}$ of ^{56}Ni per type I SN.

The reasons for believing that a thermonuclear explosion disrupts the whole star are:

1. Stellar evolution calculations predict the formation of a degenerate carbon oxygen core whose early ignition would explode the star.
2. No soft x-ray source (cooling neutron star) or pulsar is seen at the site of Tycho¹³ or Kepler's SN remnants.¹⁴

We examine some of these reasons for low mass ejecta (1-5) in greater detail because they determine the likelihood that positrons from supernova can contribute to the galactic center annihilation radiation.

(1) Doppler velocities of the type I SN ejecta are inferred from the line shifts. To obtain these requires an interpretation of the spectra. The most convincing interpretation is that of Branch¹² and colleagues who superimpose absorption lines on a continuum emission from a photosphere. They estimate an expansion velocity of 10^9 cm s^{-1} for the photosphere at its maximum radius at 30 days after maximum light or 45 days after the supernova origin. We can estimate the thickness and hence outer radius of the matter distribution on the basis of assuming a uniform expansion and an opacity as great outside as inside the photosphere and the Eddington surface approximation. The result is that the velocity of the surface of the uniform region becomes $1.5 \times 10^9 \text{ cm s}^{-1}$. Using the above and the fact that the maximum occurs at roughly 45 days results in an ejected mass $0.14/\kappa$ solar masses. The opacity, κ , unfortunately, is most uncertain because of the line scattering and doppler shifts. It could be as low as the compton cross section $\times 1/\langle A \rangle$, A the average atomic weight, and hence $< 10^{-2} \text{ cm}^2 \text{ g}^{-1}$. On the other hand Karp et al.¹⁵ have estimated opacities significantly greater than compton for smaller doppler shifts. Here very small changes in composition, temperature and doppler velocities make large changes in opacity.

(2) Several low mass, binary pulsars and one low mass fast pulsating x-ray source are known. It is highly unlikely that these binaries can be formed in a type II supernova because the mass ejected is greater than the mass of the sum of the residual stars. An alternate mechanism to produce neutron stars unobservably seems unlikely when collapse inside a $10 M_{\odot}$ envelope (SN II) manages to eject the envelope rather than collapsing the envelope to a black hole. In other words if collapse to a neutron star ejects matter in one case with a massive envelope, then collapse with a much less massive envelope should eject some matter more easily. A very small ejected mass will make an observable supernova.

(3) The exponential light curve of SN I is well known to give a constant exponential decrement from roughly 100 days to ≈ 700 days after maximum luminosity with a half of $56 \pm$ (a few) days. The uniqueness of the exponential behavior is open to some question, especially when one attempts to average the very large data base of SN I light curves assembled by Barbon et al.¹⁶ Similarly a scatter of decay times is presented by Rust et al.¹⁷ However, as is even evident from their Table I whenever the late time light curve is measured with high accuracy, the value of the decay half-life approaches 56 days with significantly greater accuracy. One surmises that the very brightest supernova are measured most carefully because of the potential for a more meaningful data set. The 56-day half life is observed with better than 5% accuracy for IC4182 (1937c), NGC4214 (1954a), NGC5253 (1972e). These are the only cases in which a data point beyond 600 days (after maximum) was measured. These data points are shown in Figs. 1 and 2 from ref. 3 with the 700-day data point of 5253 emphasized as well as the corresponding ones for 4182. These points were obtained after great effort; the first photometric by Kirshner and Oke¹⁸ and the second photographic by Deutsch as reported by Van Hise¹⁹ and Baade and Zwicky.²⁰ The late time exponential decay, when measured accurately extends over a range of luminosity of 10^3 . There are examples of fainter type I supernova light curves less accurately measured that do not demonstrate this striking feature, but where there is the potential for observation, the exponential feature occurs.

We have interpreted this feature as being due to the progressive escape of positrons^{2,3} from the expanding debris. Figures. 1 and 2 are from ref. 3 where the deposition function for both gamma rays and positrons were calculated with a Monte Carlo numerical calculation. This deposition calculation shows that in a region of expansion appropriate to the problem, an exponential radioactive decay was transformed into a half life roughly 3/4 of the nuclear decay half life (77 d for ^{56}Co). The factor 3/4 is a fortuitous circumstance previously noted but unexplained.¹⁹

The alternate explanation of this phenomena has been put forth for the thermonuclear explosion models.⁴ Here, because the escape fraction is small or an assumed closed magnetic field within the uniform density region of the ejecta, leads to the assumption of fully trapped positrons.

If there were no other losses, then one obtains the dashed curve in Fig. 2 for the luminosity corresponding to the 77-day half life of ^{56}Co positrons. One observes that something like a factor of 10 loss must be introduced to reduce the positron luminosity source to the observed luminosity decay.

Axelrod⁴ has proposed that the reduction in late time luminosity occurs due to infrared emission. This produces the curve with the dotted cutoff. The reason for the sudden transition is derived in Meyerott²¹ where he shows that the infrared emission states in Fe II and Fe II* are strongly saturated and hence result in an emission relatively independent of density whereas the optical emissivity is density dependent, his Figs. 6 and 7. Hence the transition from optical to infrared emission will occur suddenly in time as shown in

FIG. 1.—The calculated luminosity at early and intermediate times for $M_{Ni} = 0.25$ solar masses and the corresponding deposition functions for $\tau = 1$ at 20 days and 40 days. Gamma-ray deposition and the $Ni \rightarrow Co \rightarrow Fe$ decay determine the solid curves. The dashed curve is the modification of the deposition function due to diffusion and expansion (Colgate and McKee 1969). The extrapolation of the deposition curves reaches 2×10^{41} ergs s^{-1} at $t = 0$, and the difference between this and the dashed curve is due to heat energy converted to kinetic by expansion. The circles give NGC 5253 data (Kirshner and Oke 1975), and the squares give NGC 4182 data (Baade and Zwicky 1938; Van Hise 1974).

FIG. 2.—Same as Fig. 1 for times out to 700 days. Here the curves are primarily determined by the deposition of positrons from the $Co \rightarrow Fe$ decay. The dashed curve is a fit to the data with a slope corresponding to a 56 day half-life.

Fig. 2. The infrared emission depends upon the low lying levels in Fe II and Fe III at wave lengths of roughly 23 and 33 microns. The excitation of these levels can take place by relatively low energy electrons, $\cong 0.1$ eV, and so a large infrared radiation flux saturated in the lines will take place at relatively low temperature. However, if the density at late times is such that the emissivity in the optical is low, then the temperature will increase. This higher temperature will then ionize Fe III to Fe IV and no further infrared emission will take place. I estimate that for the expected conditions that the temperature maximizes a second time at roughly one year ($15,000^\circ$) and is $\times 3$ higher than necessary to ionize Fe III to Fe IV. I believe this is what happens with the low mass high velocity expansion conditions of the neutron star SN I model.

(4) The peak luminosity of SN I has been interpreted by Branch in terms of distance, red shift and ejected mass of ^{56}Ni . The value he derives is $H \cong (M_{Ni}/M_\odot)^{-1/4} \text{ km s}^{-1} \text{ Mpc}^{-1}$. For a full white dwarf mass

of $1.4 M_{\odot}$ of ^{56}Ni this corresponds to $H = 34$ and $0.7 M_{\odot} ^{56}\text{Ni}$ to $\cong 50$. The $\frac{1}{2} M_{\odot}$ of ^{56}Ni , neutron star model results in $H \cong 80$. The continuing debate on the correct value of H may yet resolve supernova or be resolved by them.

(5) The iron synthesized by SN I is bounded by the likely amount of iron in the solar neighborhood¹¹ and places an upper bound of $0.3 M_{\odot}$ of iron per all supernova. Since SN II should produce some iron, this restricts SN I models to low mass ejecta.

LACK OF OTHER GAMMA RAYS

The spectra of radiation from the galactic center shows no other gamma ray lines to roughly 10% of the annihilation peak. The greatest sensitivity to the gamma ray lines of $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ decay is the gamma ray of 0.84 MeV that is emitted each transition. Thus there will be 2/5 as many annihilation quanta per decay as the 0.84 gamma rays. The lower limit background instantaneous rate of 1×10^{-4} photon $\text{cm}^{-2} \text{s}^{-1}$ from the galactic center requires that the neutron star model of $0.25 M_{\odot}$ of ^{56}Ni has decayed by 2×10^{-6} , or observed after a time of 13 life times or 4 years. This 4-year delay must precede the earliest observations of roughly 10 years ago.

Therefore we are observing at least 14 years after such a possible event. On the other hand only a fraction 4×10^{-3} of the emitted positrons need to annihilate during the one year peak so that the escape positrons may run into a local molecular cloud whose density gradient is large and solid angle small to result in the observed peak. The possibility of such a SN I event occurring 15 to 20 years ago in the galactic center and not being observed in some wave length would seem possible but unlikely.

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