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ELECTROMAGNETIC CASCADES IN THE MAGNETOSPHERE OF A VERY YOUNG PULSAR: A MODEL FOR THE POSITRON PRODUCTION NEAR THE GALACTIC CENTER

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ABSTRACT

We propose a model for the positron production required by the 511 keV annihilation line observed from the Galactic center. The model requires that a young pulsar, presumably arising from a recent ($\lesssim$200 yr) supernova explosion, lies within the central parsec of our Galaxy. The proposed pulsar has a high surface temperature ($T \approx 10^7$ K), which results in the generation of an intense field of soft X-ray photons leaving the neutron star. Interactions between these photons and highly relativistic electrons produce electromagnetic cascades in the pulsar's magnetosphere. Electron-positron pairs are produced in these cascades, principally through electron-photon interactions (triplet pair production) and photon-photon pair production. Triplet pair production, under certain conditions, yields relatively low energy (100–1000 MeV) pairs. In addition, the pairs lose energy to Compton scattering off the soft X-rays. The gamma rays thus produced are beamed along the open magnetic field lines. The absence of pulsed γ-ray emission from the Galactic center is then explained by the low probability ($\sim$10%) that the beam sweeps across the line of sight. The positrons leave the source and eventually diffuse to the surrounding medium where they annihilate. This yields a low detected ratio of gamma-ray continuum to annihilation radiation, as is observed.

Subject headings: elementary particles — galaxies: nuclei — gamma rays: general — pulsars — radiation mechanisms

I. INTRODUCTION

The 511 keV positron annihilation line observed from the Galactic center appears narrow (width < 2.5 keV), bright (luminosity $\approx 2 \times 10^{37}$ ergs s^{-1}), and variable ($\leq$100 days) (see Lingenfelter and Ramaty 1982 for a review). These observations severely constrain the nature of the positron source. In addition, the high line to >1 MeV continuum ratio implies a very efficient pair production mechanism or, alternatively, some beaming of the γ-ray continuum out of the line of sight. Moreover, there is strong evidence that the source of annihilation radiation is also responsible for the hard (>50 keV) X-ray emission observed from the Galactic center (Leventhal *et al.* 1980).

Many models have been proposed thus far to explain the positron production. Lingenfelter and Ramaty (1982) give a complete review of the various models. Typical radio pulsars producing pairs by means of their strong magnetic fields (Sturrock 1971) cannot exceed rates of $\sim 10^{36} e^+$ s^{-1}. Even in the extreme case of a 1 ms pulsar the rate is $\sim 10^{42} e^+$ s^{-1} (Arons 1983). On the other hand, multiple sources (e.g., many pulsars) cannot explain the observed variability in the intensity of the line. This leads some authors to favor a black hole model with mass ranging from $10^2\ M_\odot$ (Lingenfelter and Ramaty 1983; Ozernoy 1979) up to $10^6\ M_\odot$ (Blandford 1982; Burns 1983). The black hole model seems attractive since, apart from explaining the positron source, it also provides a model for the central engine of the Galactic center similar to that proposed for other, more active galactic nuclei (Rees 1982).

At first glance, it would appear that the most favorable positron production mechanism would be photon-photon pair production, since it is relatively more efficient than the other competing pair production mechanisms. In this process, the most efficient pair production occurs for photon energies close to mc^2. This forms the basis of the model, proposed by Lingenfelter and Ramaty (1983), in which positrons are produced by isotropic photon-photon interactions. The interacting photons ($\sim$a few MeV) are provided by a hot accretion disk around a small ($\sim 10^2\ M_\odot$) black hole. Alternatively, Burns (1983), in a model in some ways similar to the one described here, proposed that positrons be produced from small angle interactions in a relativistic jet which in turn might arise from the dynamo action of an accreting, massive ($\sim 10^6\ M_\odot$) black hole. In another model involving massive black holes and photon-photon interactions, Blandford (1983) considered GeV-Comptonized photons interacting with keV synchrotron photons. However, most of these models suffer from the fact that since the efficiency for photon-photon pair production falls off as E^{-2}, the process is efficient only for photon energies close to threshold. Moreover, low-energy pairs can be copiously produced only through interactions in which both photons have energies less than a few MeV. The combined requirements of high efficiency and low energies of the pairs can therefore be satisfied only in a very narrow energy region. Those models which consider isotropic geometries result in hard X-ray and γ-ray continuum luminosities which exceed those observed from the Galactic center, since the produced positrons must lose their energies radiatively before they form positronium and annihilate.

Although some authors insist that the velocity distribution of gas in the nuclear region of the Galaxy constitutes observational evidence for the presence of a black hole with mass $> 10^6\ M_\odot$ at the Galactic center (e.g., Serabyn and Lacy 1985; Lo and Claussen 1983; Lo *et al.* 1985), the interpretation of the gas motions in the Sagittarius region is not straightforward. Moreover, Ozernoy (1976) has argued that a massive black hole would disrupt stars at a rate higher than observations allow (see, however, Rees 1982). Furthermore, the black hole model does not, by itself, explain the ionization of the expanding gas clouds observed by Lacy *et al.* (1980). In order for a single source to ionize the clouds to the observed degree, it would need a temperature $\sim$31,000 K and luminosity $\sim 8 \times 10^7 L_\odot$. This exceeds the observational limit (1–3) $\times 10^7$ $L_\odot$ (Becklin, Gatley, and Werner 1982). In addition, the 2.2 μm continuum would be at least an order of magnitude brighter than any individual source observed in the Galactic center (Lacy, Townes, and Hollenbach 1982). Allen and Sanders (1986) have reviewed all the evidence for a black hole at the Galactic center and conclude that, if one is present, its mass is $\lesssim 100 M_\odot$.

Not all authors have preferred models invoking a black hole at the Galactic center. Shklovskii (1983) has proposed that the total activity observed from the Galactic center could be attributed to a supernova that exploded there $\sim$100 yr ago. In addition, Ozernoy (1976) and Davies, Walsh, and Booth (1976) have argued that the activity observed from the Galactic center can be attributed to a young pulsar. Reynolds and McKee (1980) have modeled the compact radio source Sgr A* as a relativistic wind or jet generated by a central pulsar. Lo *et al.* (1981) reject this, arguing that the proper motion of a pulsar with a "characteristic age" of 10^6 yr would then displace it by 0°.5 from its birthplace, and hence the positional coincidence with IRS 16 would be fortuitous. Also, the discovery of the positron annihilation radiation has cast doubt on the pulsar model: radio pulsars cannot explain the observed rate. If the pulsar is young, however, as we propose here, its displacement from its birthplace should be about that observed between Sgr A* and IRS 16C, 1".2 ± 0".5 (Tollestrup, Capps, and Becklin 1986). Furthermore, Brecher, and Mastichiadis (1983) showed in a preliminary study that it might be possible for a pulsar to provide the positrons required to produce the annihilation radiation, if the neutron star is sufficiently young and hot. They predicted that in this case its age should not exceed $\sim$100 yr, in agreement with Shklovskii.

We present here a detailed model for positron production by a young pulsar. In § II we show that electromagnetic cascades can develop in a young pulsar's magnetosphere and apply the results to the pulsar which we hypothesize to lie near the Galactic center. We find that such a pulsar would be expected to produce relatively low energy electron-positron pairs with an efficiency high enough to explain the observed luminosity of the Galactic center annihilation line. In addition, virtually all of the γ-ray continuum radiation produced in the cascades would be beamed along the magnetic poles of the neutron star, and therefore would be unlikely to be observed from Earth. In § III we discuss these results, and in § IV we give some observational predictions generated by our proposed model for the Galactic center positron source.

II. PHYSICAL PROCESSES IN THE MAGNETOSPHERE OF A YOUNG PULSAR

Calculations of the thermal evolution of a neutron star have shown that the surface temperature of a young pulsar (younger than 200 yr) can be as high as $\sim 10^7$ K (Tsuruta *et al.* 1972). This results in an intense quasi-blackbody photon field of average energy of $\sim$2 keV. As is the case for older radio pulsars, a young pulsar is expected to have a high nonthermal energy output in the form of highly relativistic electrons. (For example, the Crab nebula is filled with relativistic electrons which must be supplied by the pulsar; Manchester and Taylor 1977, p. 64.) If the acceleration of the particles occurs close to the surface of the star, interactions between the relativistic electrons and the ambient, thermal photons can initiate intense electromagnetic cascades. If the temperature is high enough ($T \gtrsim 10^7$ K), triplet pair production short circuits the gap before the primary electrons can reach energies at which magnetic pair production (Sturrock 1971) becomes dominant. (The importance of positron-electron pair production resulting from the interaction between particles and photons in pulsar magnetospheres was first proposed by Cheng and Ruderman 1977.) Thus the behavior of young pulsars must be different from that of their older counterparts. For calculational purposes we have chosen the outer gap model as initially proposed by Holloway (1973) and Cheng, Ruderman, and Sutherland (1976), but the results should hold (at least qualitatively) for other acceleration models as long as the acceleration region is close to the surface of the neutron star.

Since the pair production is most intense when it occurs near the surface of the neutron star, we require that the axis of rotation make a large angle to the magnetic moment vector; an outer gap can then be formed just above the pulsar's polar cap. (If $\boldsymbol{\Omega}$ and $\boldsymbol{B}$ were parallel, then the smallest distance at which an outer gap could form would be close to the light cylinder.) In our discussion we treat separately the physical processes inside and outside the gap. (In the former case the particles are accelerated to high energies even as they collide with the ambient photons, while in the latter the particles lose energy without being reaccelerated as they diffuse outward.) We assume throughout that the magnetic field has a dipolar configuration and that the particle trajectories follow the open field lines along the magnetic poles.

a) Physical Processes inside the Gap

Mestel (1971) showed that the charge density in a pulsar magnetosphere is, for a general oblique-rotator geometry,

$$\rho_e = -\left(\frac{\boldsymbol{\Omega} \cdot \boldsymbol{B}}{2\pi c}\right) + O\left(\frac{v^2}{c^2}\right), \tag{1}$$

where Ω is the spin of the neutron star, B is its magnetic field, and v is the rotational speed of its surface. At positions where $\boldsymbol{\Omega} \cdot \boldsymbol{B} \approx 0$ the charge density vanishes and the open magnetic field lines which intersect this locus should change sign. Since particles of opposite signs are flowing away from this region, one might expect a depletion of charges and a consequent formation of a potential difference. These "outer gaps" were first proposed by Holloway (1973). Cheng, Ruderman, and Sutherland (1976) showed that the "outer" gap actually lies quite close to the surface of the star for an oblique rotator. The potential drop across such a gap is of order

$$\Delta V \approx \frac{\Omega B_s R^3 h^3}{c r^4}, \tag{2}$$

where B_s is the magnetic field at the star's surface, R is the stellar radius, h is the thickness of the gap, and r is the distance of the gap from the pulsar. For the case we are considering we can set $r \approx R$, so equation (2) can be rewritten for the usual pulsar parameters

$$\Delta V = 2 \times 10^{10} B_{12} R_6^{-1} P_{-2}^{-2} h_4^3 \text{ statvolts}, \tag{3}$$

where B_{12} is the magnetic field in units of 10^{12} G, R_6 is the radius in units of 10^6 cm, P_{-2} is the rotation period in units of 10^{-2} s, and h_4 is the gap height in units of 10^4 cm. For definiteness we consider the magnetic pole for which the potential causes electrons to flow outward. The electrons inside the gap are accelerated to an energy

$$E_0 \approx 6000 B_{12} R_6^{-1} P_{-2}^{-\frac{1}{2}} h_4^3(x/h) \text{ GeV} \quad (4)$$

after traversing a distance x within the gap. It can be shown that energy losses (mostly from triplet pair production and Compton scattering) cannot limit the acceleration of the electrons inside the gap. Rather the acceleration ceases when so many pairs are produced that the gap is shorted out. This occurs when the electrons have traversed a distance roughly equal to the mean free path to pair production. Using the total triplet cross section given by Mastichiadis, Marscher, and Brecher (1986, hereafter Paper I) and assuming that the photon distribution is nearly that of a blackbody (with a corresponding photon density $n_\gamma = 2 \times 10^{22}(R/r)^2 T_7^3 \text{ cm}^{-3}$), we find that

$$x_{\text{triplet}} \approx (n_\gamma \sigma_{\text{triplet}})^{-1} \approx 1 \times 10^4 (r/R)^2 T_7^{-3} \text{ cm} . \quad (5)$$

From expression (4), we obtain for the emergent energy of the primary electrons

$$E_0 \approx 7 \times 10^3 B_{12} R_6^{-3} r_6^2 P_{-2}^{-\frac{1}{2}} T_7^{-3} h_4^2 \text{ GeV} . \quad (6)$$

A more accurate value requires the more detailed treatment outlined below.

The physical scenario inside the gap is then as follows: the primary electrons are accelerated to high energies, then collide with the local thermal photons. If the photons have energies greater than $4mc^2$ in the electron rest frame, a positron-electron pair is produced. The spectra of the produced particles and of the recoil electrons are calculated in Paper I. In order to calculate the ultimate spectra of particles and photons which emerge from the pulsar magnetosphere, we use the following "mean cascade" approximation. Each particle is taken to be accelerated by the potential (3) up to a distance equal to the mean free path for pair production, at which point a pair is assumed to be produced. Each of the produced particles is approximated to take on the mean energy of the corresponding spectrum, as calculated in Paper I:

$$E_{+,\text{pr}} = E_{-,\text{pr}} \approx 0.7 E_0 \alpha_0^{-0.5} , \quad (7)$$

where $E_0(x)$ is the energy of the primary electron in mc^2 units as a function of distance x from the bottom of the gap (=2000 times the value in GeV given in expression [4]), and

$$\alpha_0 = E_0 k(1 - \beta \cos \theta) \quad (8)$$

is the energy of the photon in the electron rest frame. Here k is the photon energy in units of mc^2, β is the electron's velocity in units of c, and θ is the angle of interaction. The dependence of $E_{+,\text{pr}}$ and $E_{-,\text{pr}}$ on θ is important. Head-on collisions ($\theta = \pi$) give lower energy pairs than tail-on ($\theta = 0$) (see Paper I). In the situation under consideration we have nearly tail-on collisions since both electrons and photons are moving outward. To obtain expression (7) we have integrated the differential cross section (as given by relation [15] of Paper I) over θ. The limits of the integration are given by the geometry of the problem. The recoil electron possesses a mean energy

$$E_{\text{rec}} = E_0 - 2E_{+,\text{pr}} . \quad (9)$$

A produced or recoil electron will continue to move outward, regaining energy until it again reaches an energy above the threshold for pair production, encounters a photon, and pair produces in a recurring fashion. The produced positron, on the other hand, initially decelerates (since its original momentum is outward) before eventually turning around and gaining energy as it is accelerated toward the neutron star surface. It encounters the thermal photons almost head-on, and consequently has a shorter mean-free path to pair production. An electromagnetic cascade is thus produced. Figure 1 shows the number of pairs produced per primary electron in the cascade as a function of gap height h for several temperatures. The number of pairs produced increases exponentially with the gap height until the gap is shorted out. The acceleration then stops until a new gap is formed as the electrons move outward and the positrons inward toward the surface; the entire process is then repeated.

A consequence of the above scenario is that the positrons (electrons at the opposite pole) should return to the polar cap. The positrons then lose their energy by collisions with ions within a short distance beneath the surface. Consequently, their energy is deposited there and becomes thermalized. For isolated pulsars, this process has been discussed by Cheng and Ruderman (1980), Helfand, Chanan, and Novick (1980), and Arons (1981). In any case, a large amount of the infalling energy is conducted away, but most gets thermalized and is reradiated locally from the region under the spark. Thus the temperature T of the polar cap region should be higher than that of the general surface. It is not possible to determine accurately the temperature of the area, partly because the ratio of energy deposited to that reradiated locally is unknown and partly because we do not have an estimate for the filling factor corresponding to the fraction of the polar cap area which becomes filled with the discharge. However, we can make an order of magnitude estimate by adopting the assumption that the amount of energy that is reradiated is about one-half the total incoming energy. Calculations performed with the cascade assumptions described above show that the incoming energy should be roughly equal to the outgoing energy. Furthermore, we can estimate the filling factor to be ~ 0.1. (Since we expect discharges to occur around the $\boldsymbol{\Omega} \cdot \boldsymbol{B} = 0$ cone, the parts of the polar cap [if any] that lie outside this locus will not be affected by them.) We then find that the temperature of the polar cap should rise to $\sim 7 \times 10^7$ K. This is probably an overestimate and will be treated as an upper limit. For the time being we leave the temperature of the polar cap as a free parameter. For the case of the Galactic center it is possible (in principle) to obtain an observational upper limit for the surface temperature of the putative neutron star from the soft X-ray luminosity observed from that region. If we assume that the observed soft X-rays arise from the pulsar, we can set the general surface temperature to $T \approx 10^7$ K, which gives a thermal luminosity within the observed limits ($10^{35 \pm 1}$ ergs s^{-1} from 0.5 to 4.5 keV) (Matteson 1982). However, the observational constraint on the temperature of the polar cap is much weaker owing to the lack of high-resolution observations in the 5–10 keV region.

Because of the higher temperature attained by the polar cap region, we expect more intense cascades there (since the optical depth for pair production increases with the temperature of the photon field). Hence, in order to maintain self-consistency, the gap height must decrease (since now the mean free path is smaller than before). Another important result is that pairs are produced with lower energies than previously assumed (see relation [7]). For polar temperatures $T_c \lesssim 1.5 \times 10^7$ K, the number of pairs produced by γ-e interactions is not sufficient to short out the gap, and magnetic pair production, as discussed previously in the theory of standard radio pulsars (e.g., Stur-

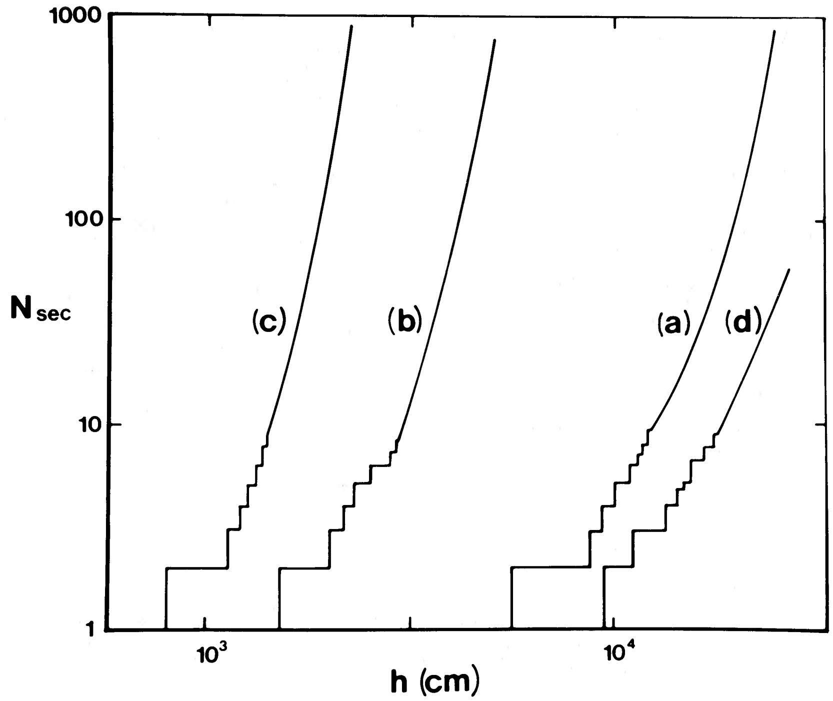

FIG. 1.—Number of pairs produced per primary electron inside the gap vs. gap height for various polar cap temperatures. (*a*) $T_c = 10^7$ K; (*b*) $T_c = 2 \times 10^7$ K; (*c*) $T_c = 3 \times 10^7$ K. Curve (*d*) represents the difference between the number of outgoing electrons and positrons (for $T_c = 10^7$ K).

rock 1971; Ruderman and Sutherland 1974), dominates. In this case it seems likely that, for the reasons explained in the above references, the pulsar will not generate positrons at the rate required to explain the Galactic center annihilation radiation.

b) *Physical Processes outside the Gap*

Once an electron (and any positron which crosses the gap before turning around) leaves the gap, it loses energy not only to pair production, but also to Compton losses as its energy decreases. In order to calculate the electromagnetic cascade during this stage, we have performed a crude Monte Carlo simulation wherein each particle is assigned a certain probability for pair production or for Compton scattering, which corresponds to the ratio of the cross sections for the two processes. The pair production case is treated as before. Since now there is no electric field to turn the positrons around, they continue to move outward along with the electrons. For the case of Compton scattering, the mean energy of the scattered γ-ray emitted is that calculated by Jones (1968), with the remaining energy given to the recoil particle. The scattered γ-ray can (1) pair produce off the magnetic field, (2) pair produce off a soft photon, (3) pair produce off an electron, (4) Compton scatter off an electron, or (5) pair produce off another γ-ray. We find that, under the physical circumstances which we consider here, only process (2) is important, at least initially. Mechanism (1) is unimportant since, despite the very large magnetic field present, the angle between the γ-ray and the magnetic field is extremely small; this greatly reduces the optical depth to magnetic pair production (Erber 1966). Only γ-rays with energies ≥ 1 TeV pair produce off the magnetic field; for $T_c \gtrsim 1.5 \times 10^7$ K very few of the particles accelerated inside the gap (and hence scattered photons) reach such energies. The rates for (3), (4), and (5) depend on the density of particles ([3], [4]) and the density of γ-rays ([5]), both of which are initially small compared with the density of the softer photons. Moreover, the mean free paths of these processes are increased since the γ-rays and particles propagate in a direction almost parallel to that of any given electron. The soft X-rays, on the other hand, interact with the γ-rays at much wider angles, and hence process (2) dominates. For simplicity, we have assumed equipartition between the produced particles, such that each one possesses half the γ-ray energy. From the above considerations, we find that outside the gap a cascade similar to that which occurs inside the gap is formed (since the properties of the cascade depend primarily on the temperature of the photon field, which remains the same). The cascade continues until the particles have energies ($\sim$150–500 MeV) below the threshold for pair production in nearly tail-on collisions with the soft X-ray photons. For the particular case we are considering, the angle of interaction is always less than 90°, with the bulk of the collisions occurring at angles well below this limit. We call this cascade "primary" since it comes from interactions of particles and γ-rays with the ambient photons. Figure 2 shows the number of pairs produced in the primary cascade as a function of initial energy of the particle for various temperatures of the photon field.

Once the energy of a particle falls below the threshold for pair production, the particle continues to scatter soft photons. The produced γ-rays can now either pair produce from collisions with other γ-rays or interact with the particles through either Compton scattering or pair production. However, these processes are now severely constrained by the geometry of the magnetic field lines, as described above. In this case both γ-γ and γ-e interactions depend sharply on the angle of interaction. For example, the parameter α_0, as it was defined in equation (5), becomes, for $E_0 \gg 1$ and $\theta \ll 1$,

$$\alpha_0 = E_0 k(1 - \beta \cos \theta) \approx \tfrac{1}{2} E_0 k \theta^2 \; . \tag{10}$$

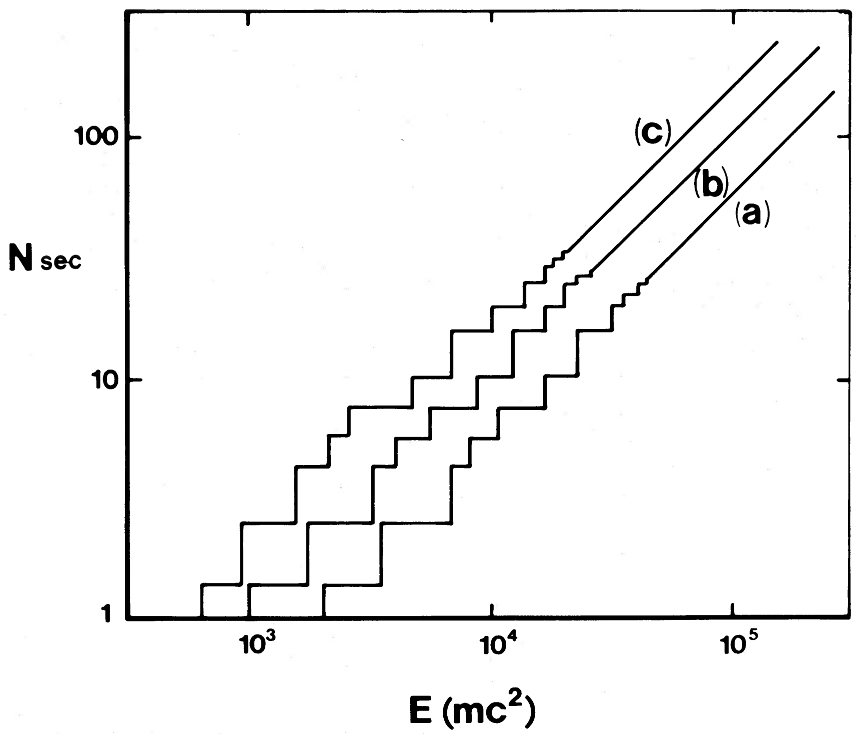

FIG. 2.—Number of secondary pairs produced in the region above the acceleration zone vs. primary electron energies for various polar cap temperatures. (*a*) $T_c = 10^7$ K; (*b*) $T_c = 2 \times 10^7$ K; (*c*) $T_c = 3 \times 10^7$ K. Both triplet pair production and photon-photon pair production are included.

Although wide-angle interactions can produce pairs, Compton scattering dominates instead, since typically $\theta \approx 10^{-4}$–10^{-2}, and the γ-ray has a relatively low energy in the electron frame (and the interaction approaches the Thomson limit). This secondary cascade reduces the particle energies to 10–100 MeV with a typical mean free path of ~ 0.5–1.0×10^5 cm.

Energy-loss mechanisms which we have omitted from the cascade are of secondary importance. Synchrotron and curvature radiation losses are greatly reduced since the pitch angles of the produced pairs (or of the recoil) are extremely small (see above). Bremsstrahlung is also unimportant, despite the large density of the particles, since the particles move along trajectories which are nearly parallel; this greatly reduces the rate of particle-particle interactions.

We have neglected aberration effects in the cascade development. This is justified since the processes discussed here occur relatively close to the pulsar's surface, where $\Omega r \ll c$; hence, complications from the pulsar's rotation can be neglected.

c) *Fate of the Produced Particles and Photons*

Once the particle energies fall below the threshold for pair production, they cool through Compton scattering off the ambient photons, whose density is still quite high (since the cascade takes place over a range $\sim 10^6$ cm). The cooled particles (energies of ~ 5–10 MeV) move along the diverging magnetic field lines away from the star. By the time the particles diffuse to the surrounding medium, their density has decreased significantly ($\sim 10^8$ cm^{-3}). According to Lingenfelter and Ramaty (1982), the annihilation region in the Galactic center must have a temperature $\lesssim 5 \times 10^4$ K, a density of $\sim 10^5$ cm^{-3}, and a $\sim 10\%$ degree of ionization, conditions which are plausible for the compact gaseous regions observed in the central regions of our Galaxy. (Brown 1985 has recently shown that it is also possible for the annihilation to occur in a neutral hydrogen medium, while Zurek 1985 has proposed that the annihilation takes place in a dusty environment.) Once the produced positrons diffuse into that region, they cool further from bremsstrahlung and ionization losses, and annihilate (either freely or after forming positronium), thus producing the observed 0.511 MeV line (see Bussard, Ramaty, and Drachman 1979).

An important consequence of our model is that the γ-rays generated by Compton scattering are very narrowly focused along the magnetic poles of the neutron star. The young neutron star should therefore be a highly luminous γ-ray pulsar. Because of the high directionality, however, the probability that we lie inside the emission cone is $\sim 10\%$. In the context of our model, it is therefore not surprising that we observe no pulsed γ-rays from the Galactic center.

d) *Summary of the Cascade*

We now summarize the basic points of the cascade. If the acceleration zone (i.e., the outer gap) occurs close the pulsar, then the time scale over which acceleration can occur (viz., the time it takes for pairs to short out the gap) inside this zone will be limited by triplet pair production of electrons off the thermal soft X-ray photons which emanate from the surface of the neutron star. The potential accelerates produced particles with charges of one sign outward and reverses the direction of particles of opposite sign such that they bombard and heat the polar cap region. Thus, a substantial amount (perhaps as high as one-half) of the total energy is deposited into the polar cap region, heating it further. This higher temperature promotes efficient pair production in the magnetosphere. Photon-particle interactions dominate outside the potential gap as well. As the energy of the particles decreases, Compton scattering becomes increasingly important, and the bulk of the pair production results from collisions between γ-ray and soft X-ray photons. The cascade continues until the γ-ray energies fall below the threshold for pair production. Geometric factors then severely limit further γ-γ and γ-e interactions, such that these processes are no longer efficient. On the other hand, since the spatial extent of the cascade is $\sim 10^5$–10^6 cm, the produced particles continue to lose energy through Compton scattering. The produced γ-rays that escape are highly collimated since most of the scattering takes place close to the surface of the star where the open magnetic field lines are almost parallel. The produced particles have energies between 5 and 10 MeV; since the positrons must lose this residual energy prior to annihilation, and will do so at least partly through the generation of bremsstrahlung γ-rays, our mechanism yields a ratio of annihilation line to γ-ray continuum luminosity ~ 0.05–0.1, in agreement with the observed value ~ 0.1 (Riegler *et al.* 1985). The ratio of pair luminosity to nonthermal luminosity can be obtained by dividing the number of pairs produced, ~ 100 per primary electron, times their final energy, ~ 5–10 MeV, by the final energy of the primary electron, ~ 100 GeV:

$$\frac{L_{\text{pairs}}}{L_{\text{nonthermal}}} \approx \frac{N_{\text{pairs}} E_{\text{pairs}}}{E_{\text{primary}}} \approx \frac{(100)(10\ \text{MeV})}{10^5\ \text{MeV}} \approx 10^{-2} \,.$$

We therefore find that a pulsar with a nonthermal energy output of $\sim 3 \times 10^{39}$ ergs s^{-1} could explain the rate of positron production observed from the Galactic center.

The importance of the triplet process to the final outcome of the cascade is twofold. Under the conditions found in the acceleration zone of a very young pulsar, it is triplet pair production which first supplies the pairs which short out the potential gap. If triplet pair production were ignored, the gap would be shorted out only after the primary electrons attain very high energies, ~ 1000 GeV or more. The number of pairs produced *per unit primary electron energy*, and therefore *per unit luminosity*, would then be greatly reduced. In addition, the presence of triplet pair production enhanced the cascades outside the gap, an effect which also increases the final number of pairs per primary electron.

III. DISCUSSION

In the previous section it was shown that a young pulsar can produce rather low energy pairs through interactions between the thermal photons from the neutron star surface and the high-energy electrons generated from the conversion of rotational to electromagnetic energy. In order for a young pulsar to be able to generate positrons at the rate observed from the Galactic center, it must possess a nonthermal luminosity $\sim 3 \times 10^{39}$ ergs s^{-1}, almost 8 times that of the Crab pulsar. This is consistent with the pulsar's assumed youth. If the pulsar is ~ 100 yr old, a significant fraction of its luminosity is in the form of gravitational radiation; hence, the deceleration parameter should be rather high during this stage (perhaps as high as ~ 2 times that of the Crab pulsar). This, plus the rapid falloff of the neutron star's surface temperature, imply that the high pair production rate should be a relatively short-lived phenomenon. We expect the rate of pair production to decrease with time. Although this could explain the sudden decline in line intensity observed in 1980–1981 (Riegler *et al.* 1981; Paciesas *et al.* 1982; Leventhal *et al.* 1982), we expect that the pulsar positron production would decrease in a slower fashion, over a time scale of roughly tens of years. Nevertheless, pulsars do tend to be variable on various time scales (for reasons which are not clear), so that it would not be particularly surprising for the emission mechanisms (including the positron production) to change erratically.

Another consequence of the model is that it predicts the absence of ultra–high-energy γ-rays such as are observed from Cygnus X-3 (Samorski and Stamm 1983; Lloyd-Evans *et al.* 1983). Because their acceleration is restricted by pair production off the ambient photons, the electrons are effectively radiation limited as they are accelerated in the gap. The polar-cap surface temperature then determines the energy of the primary electrons. The polar-cap temperature also plays an important role in the primary cascade since a significant fraction of ambient photons originates in this region. However, as the total radiation rate of the pulsar decreases with time, the polar cap temperature must drop since the incoming particle energy decreases. As a result, the cascade becomes less intense, and the mean free path for pair production increases. Ultimately, magnetic pair production dominates, since the optical depth for γ-e or γ-γ pair production decreases significantly as the pulsar moves toward adulthood.

IV. CONCLUSION

It is thus possible to explain the intensity of the electron-positron annihilation line observed from the Galactic center if a young (~ 100 yr) pulsar exists there. Shklovskii (1983) has shown that the presence of a pulsar in the Galactic center is reasonable, and that other features observed in the region could be explained as consequences of the accompanying supernova explosion. We can discriminate between this and the black hole hypothesis using the following tests: (i) pulsars are expected to have high radial velocities (Manchester and Taylor 1977). Such motion or displacement is not expected in the context of a massive black hole. Multiepoch measurements of the separation between IRS 16 and the Sgr A West radio source should determine whether the predicted motion is occurring. (ii) The pulsar hypothesis predicts that the mean line intensity must eventually (time scale of roughly tens of years) decrease with time. The black hole model makes no such prediction. Further observations over several decades would prove decisive (if, in fact, the recent low intensity is a transient state).

Finally, if correct, the pulsar hypothesis negates the notion that the Galactic center represents a scaled-down version of other active galactic nuclei (see also Marscher *et al.* 1984).

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