PARTICLE ACCELERATION BY PULSARS

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ABSTRACT

The evidence that pulsars accelerate relativistic particles is reviewed, with emphasis on the γ-ray observations. The current state of knowledge of acceleration in strong waves is summarized, with emphasis on the inability of consistent theories to accelerate very high energy particles without converting too much energy into high energy photons. The state of viable models for pair creation by pulsars is summarized, with the conclusion that pulsars very likely lose rotational energy in winds instead of in superluminous strong waves. The relation of the pair creation models to γ-ray observations and to soft X-ray observations of pulsars is outlined, with the conclusion that energetically viable models may exist, but none have yet yielded useful agreement with the extant data. Some paths for overcoming present problems are discussed.

The relation of the favored models to cosmic rays is discussed. It is pointed out that the pairs made by the models may have observable consequences for observation of positrons in the local cosmic ray flux and for observations of the 511 keV line from the interstellar medium. Another new point is that asymmetry of plasma supply from at least one of the models may qualitatively explain the gross asymmetry of the X-ray emission from the Crab nebula. It is also argued that acceleration of cosmic ray nuclei by pulsars, while energetically possible, can occur only at the boundary of the bubbles blown by the pulsars, if the cosmic ray composition is to be anything like that of the known source spectrum.

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I - INTRODUCTION

In this paper, I will (1) discuss the existing evidence that shows pulsars accelerate relativistic particles, (2) describe the theory of such particle acceleration, paying close attention only to internally consistent scenarios and models, and (3) use the models to assess the possibility of pulsars being the origin of cosmic rays. In § II, I summarize the evidence, emphasizing the importance of γ-ray observations as our only probe of energetic significance into the basic workings of the rotating magnetosphere. In § III, I discuss (a) the theory of pulsar spin down, (b) the scenario of particle acceleration in "strong" waves in the "wave" zone of the magnetosphere, and (c) theories of electrostatic acceleration of ultrarelativistic beams and the creation of pairs in the near zone. My conclusion is that extant models for acceleration in the near zone imply the spindown occurs through the formation of a dense, relativistic magnetohydrodynamic wind ; the strong wave model as commonly used in the cosmic ray literature does not apply. I also show that some aspects of these models may be testable by soft X-ray observations, and that no acceleration model has yet succeeded in accounting for the observations of pulsed γ-rays. I then apply these models to the problem of cosmic ray origins in § IV. I argue that direct acceleration from the surface of the neutron star, or from the near or wind zones of the magnetosphere, do not contribute to the nucleonic component cosmic rays, but I do show that observations of the positronic component of the galactic cosmic ray flux and of the 511 keV recombination line from the interstellar medium may put useful constraints on the pulsar models and/or may be explained by pulsars as the primary source of the positrons.

I also argue that the boundary layer where the relativistic winds from young, rapidly rotating pulsars interact with the surrounding interstellarmedium/supernova remnants is an energetically viable site for the acceleration of the cosmic ray nuclei.

II - OBSERVATIONS OF DIRECT RELEVANCE TO PARTICLE ACCELERATION BY PULSARS

Alsmost all pulsars are known as radio sources (see the review volume by Manchester and Taylor, 1977). Because of the short duration and low frequency of the pulses and the galactic distances to the sources, one readily concludes that a collective emission mechanism is required. For example, some pulsars broadcast essentially all their radio emission in "micropulses" of duration < 100 μsec, from which one can conclude that brightness temperatures in excess of 10^{28} K probably are required (see Cordes, 1979 for a review). Since the emission is collective, there is no requirement that the emitting medium be relativistic ; beamed, high brightness temperature radio emission occurs in the terrestrial magnetosphere with surprisingly high efficiency, for example, without involving any relativistic particles. However, the optical and X-ray synchrotron emission from the Crab nebula points obliquely toward relativistic particles being associated with pulsars, while the observations of γ-ray pulses ($h\nu > 30$ MeV) from several radio pulsars implies ultrarelativistic particles exist quite near the neutron stars.

(a) Crab Nebula

The fact that the nebular X-ray source requires continuous acceleration of relativistic electrons in well known, as is the fact that the pulsar's total rotational energy loss is sufficient to power the nebular emission (see for example, IAU Symposium No. 46 for reviews of the situation 10 years ago). The assumption of synchrotron emission was confirmed by the detection of polarization in the nebular X-rays (Novick et al., 1972 ; to prove the synchrotron hypothesis would require detection of circular polarization, impossible in practice in the X-ray region, and perhaps impossible in principle if the emitters in the X-ray emission zone are $e^{\pm}$ pairs, as is quite likely). The nebula requires at least 10^{38} erg/s to explain the photon emission ; the pulsar's spin down supplies $4\pi^2 I\dot{P}P^{-3} = 5 \times 10^{38}$ $(I/10^{45}$ g.cm$^2)$ ergs.s^{-1} with I the moment of inertia, P = $0^s.033$ the pulsar rotation period, and $\dot{P} = 4.3 \times 10^{-13}$ s/s the spindown rate. Thus the pulsar supplies the energy needed in some unknown form, mostly to be absorbed by the nebula on the south west side of the pulsar (Ricker et al., 1975 ; Giacconi, 1979). The fact that $I \sim 10^{45}$ g.cm^2 is needed to give the requisite output is the strongest support of the rotating neutron star hypothesis. The fact that the excitation of the nebula is so one sided may be a peculiarity of the pair creation by the pulsar, to which I return below.

However, this observation does not tell us whether the pulsar puts its energy into $\sim 10^{38}$ electrons/sec with energy ~ 1 TeV, then shoots them into the nebula, or if the pulsar emits the energy in some lower entropy form which is reprocessed in the nebula into relativistic particles. Put differently, we don't know if the nebular electrons are injected or are accelerated in situ. There are many handwaving models of both types, all unsatisfactory to my way of thinking. One way of proceeding is to see if we can understand the pulsar a bit better. For this, the γ-ray observations of pulses are invaluable.

(b) Pulsed γ-rays

Satellite observations (Thompson et al., 1975 ; Bennett et al., 1977 ; Kanbach et al., 1980) have clearly established the emission of pulsed γ-rays from the Crab and Vela pulsars with luminosities $\sim 10^{35}$ erg.s^{-1} and $\sim 10^{33.5}$ erg.s^{-1} respectively. In addition, 3 σ results and/or upper limits have been reported for several other pulsars (Ogelman et al., 1976 ; Thompson et al., 1976 ; Kanbach et al., 1977 ; Mandrou et al., 1980). I will use only the Crab and Vela in my discussion, as only here are there clearly established results.

For the Crab pulsar, the essential facts are that the optical, X- and γ-ray pulses are coincident to within the timing errors, and coincide with the main radio pulse and interpulse. 15 μsec time resolution is needed to resolve the peak of the optical pulse (Smith et al., 1978) ; the X-ray pulse is unresolved at 60 μsec. The total O, X and γ output is about 0.03 % of the total spin down luminosity (this is still orders of magnitude brighter than the radio emission), with a spectral slope in the X-rays and γ-rays somewhat flatter than the nebular emission. The optical emission is polarized, indicating an emission mechanism involving a magnetic field, and its intensity level is appropriate for the optical emission to be the Rayleigh-Jeans tail of the X-ray spectrum (Shklovsky, 1970). This fact strikes me as strong support for the optical emission being incoherent radiation from relativistic particles (these are needed since the brightness temperature in the optical is above 10^{11} K), despite a number of well known difficulties with this interpretation ; coherent mechanisms (eg, Sturrock, Petrosion and Truk, 1975) explain the coincidence between the optical spectrum and the RJ tail of the X-rays as a coincidence.

Granted the incoherent interpretation of the optical flux, one can make some simple inferences, all of them old (Goldreich et al., 1972 ; Epstein and Petrosian, 1974). Since the optical intensity must not exceed the black body limit, the area of the optical emission zone must be much larger than that of a neutron star. Therefore, the emission region must be well above the star. Since all of the pulses are coincident (to within the timing errors), the emission region must be at high altitude for all frequencies (radii r >> 10 km). This argument does not apply to the radio precursor, of course. If the emission region is fixed with respect to the star, so that pulses are due exclusively to stellar rotation plus some sort of beaming, the angular and radial extent of the emission region must be small, otherwise sharply cusped pulses cannot be generated. Furthermore, the emission region cannot fluctuate by more than a few % in beaming angle or radius, otherwise the averaged pulses (all that is observed at high frequency) would not show cusped structure. Finally, and obviously, the emission zone must contain relativistic particles of energy > 10 GeV, since the observed photon spectrum extends to these energies and a coherent process is exceedingly hard to contrive for wavelengths less than the Compton wavelength. The particles may or may not be accelerated within the emission zone itself. Ultra high energy γ-rays ($h\nu$ > 500 GeV reported by Grindlay et al., 1976) most likely refer to a different region, since the rotation phase of this emission differs from all the rest.

Unfortunately, the Vela pulsar is different. There is no X-ray pulse known (see Kanbach et al., 1980, for a review of the observational situation), the single radio pulse looks like the Crab's precursor, while the twin optical pulses lie between the two γ-ray pulses. This morphology might be viewed as similar to the Crab, if the Crab's main radio pulse and interpulse are regarded as unusual, while the Crab's precursor is the normal radio pulse (quite possibly true, based on comparison of the radio spectra to other pulsars). The remainder of the transformation of the Crab into Vela comes from supposing the optical and γ-ray pulses to be emitted with a hollow cone pattern with beaming along dipolar field lines (see below), with optical emission in Vela coming from a substantially smaller radius than applies to the γ-ray emission, while for the Crab, the radii of emission are much closer together. The physics behind this may be that the emission is synchrotron emission, radiation reaction is stronger at low altitude, where the magnetic field is stronger, which may allow higher particle energies and γ-ray emission only at high altitudes. In the case of the Crab, the much stronger energization might lead to the regions being closer together, so that they look like a single zone, within the resolution of γ-ray waveform. This idea predicts that the centroids of the optical pulses in the Crab should have a slightly smaller phase separation than the centroids of the γ-ray pulses, something that has not been carefully studied, so far as I known. The lack of an X-ray pulse in Vela is the main embarrassment for this picture, and probably can be explained only by a rather strong dependence of excitation of the particles' gyrational energy on period and field strength. As I will discuss, the efficiency of acceleration along B does have a very strong period dependence in the models I favor.

Vela converts ~ 0.15 % of its rotational energy loss into γ-ray emission, to give a γ-ray luminosity in the vicinity of 10^{34} erg.s^{-1} with a power law γ-ray spectrum somewhat flatter than the Crab pulsar's. There is no direct necessity to place the emission region at high altitudes, but I will show that conversion of this much energy into accelerated particles probably forces one to altitudes large compared to 10 km. Like the Crab, the γ-ray pulses in Vela are separated by about 140° of longitude. Such pulse-interpulse structure is usually thought to mean that the emission comes from field lines connected to opposite magnetic poles. However, an alternative, and I think better, interpretation comes from the radio astronomers and the theorists. It has proved possible to organize the vast zoo of pulsar light curves ("waveforms") with a simple kinematic model (Backer, 1976), in which the emission comes from a hollow cone rigidly rotating with the star, as shown in Figure 1. Emission is hypothesized to arise only in the annular rim of the cone. An observer whose trajectory is as shown in A then sees a double pulse, while a trajectory like B produces a single pulse. Note that in this picture, sharp pulses are produced because of strong localization of the beaming in angle, a property of an emission region contained in a right circular cone.

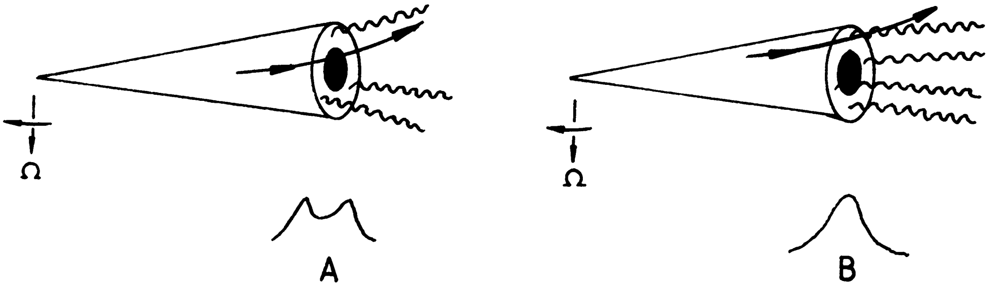

Figure 1. The hollow cone model.

In the original work, the opening angle was picked to accomodate the known separation seen in pulsars with double pulses ($\sim$ 20° is typical). Manchester and Lyne (1977) pointed out, however, that if the half angle of the cone is large (70°, for example), the 140° phase separation of the Crab pulsar could be understood within the same context. Some justification for this comes from the polar beaming model, in which pulsar emission is due to relativistic particles streaming out relativistically along approximately dipolar field lines whose opening angle increases in proportion to $r^{1/2}$, as shown in Figure 2. Note that if radiation is beamed along field lines of the

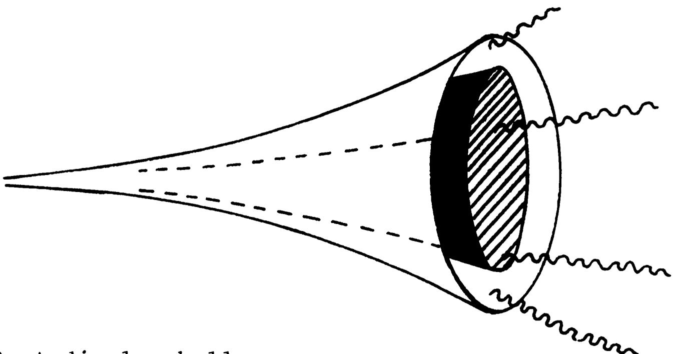

Figure 2. A dipolar hollow cone.

annular rim of this widening cone, an observer sees radiation from different radii at different phases, in contrast to the right circular cone of Figure 1. Therefore, an observer with a broad band detector (such as a spark chamber) will receive sharp pulses only if the emission region is localized in radius, as well as being localized to the annular rim of the polar field lines A narrow band detector, such as a radio receiver, will see a sharp pulse if the emission is also narrow band with each frequency associated with a given radius even if the bolometric radio emission is not radially localized, or if all the radio emission is radially localized . If such localization occurs at high altitude (r a fraction more than 0.1 of $cP/2\pi$ = 48 000 P km), half angles as large as 70° are quite possible. For more discussion of these ideas, including the statistical evidence for the applica-

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bility of very wide hollow cones and the fragments of theoretical foundation for the idea, see Manchester and Lyne (1977), Manchester (1978) and Arons (1979).

III - THEORY

The γ-ray observations certainly do show that relativistic particles are present in some region near the pulsar where the magnetic field can confine the acceleration and emission to a restricted region. (I will assume the existence of pulses is not due to a relativistically expanding sheet or sphere, where time compression can make the emission appear pulsed. This idea, first proposed by Michel and Tucker (1969), has various virtues and problems discussed by Michel (1971) and Arons (1979) which are not worth addressing here). The fact that pulsars lose angular momentum strongly suggests the presence of large scale electric fields in the magnetosphere. The fact that particle are accelerated to ultra relativistic energies near the pulsar probably requires the existence of substantial components of E parallel to $\underline{B}$. This systematic acceleration of particles in $E_{||} \equiv \underline{E}.\underline{B}/B$ actually has been discussed mostly on theoretical grounds, well in advance of the γ-ray observations, and remains the main possibility for explaining the particles which emit gamma rays. As we will see, this mechanism may be energetically sufficient, but the resulting models have not (yet) succeeded in explaining the data. By contrast, almost all work on cosmic ray acceleration by pulsars has invoked the electric fields of "strong waves", which I think are a failure.

(a) Pulsar spin down

Pulsar wave forms define an excellent clock with characteristic period P. In all well studied cases, P slowly increases at the rate $\dot{P}$. Typically, $\dot{P} \sim 10^{-15}$ s/s, but a substantial number of pulsars have large $\dot{P}$ ($\sim 10^{-13}$ s/s) and small $\dot{P}$ ($\sim 10^{-17}$ s/s). There is no correlation of $\dot{P}$ with P ; there exist a few very short period pulsars with very small $\dot{P}$, and there is a substantial group of long period objects with large values of the spin down rates. Thus evolution in the $\dot{P}$-P diagram along evolutionary tracks starting from the same initial conditions seems unlikely, although the certainty of any interpretation is poor because of the uncertain selection effects in the published data (see Manchester and Taylor, 1977), a situation which will change upon completion of the Molonglo-NRAO survey.

The fact that pulsars keep time so well and slow down steadily has been the main support of the rotating magnetized neutron star hypothesis. The reason is that a massive flywhell keeps excellent time and, when endowed with a suitable electromagnetic field, has an average spin down like that of the observed stars. An observation of P and $\dot{P}$ yields the total energy loss :

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$$\dot{E}_{rot} = \frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = -4\pi^2 \frac{I\dot{P}}{P^3} = 3 \times 10^{32} \frac{I}{10^{45}\ \mathrm{g.cm}^2} \frac{\dot{P}}{10^{-15}} \left(\frac{0.5}{P}\right)^3 \mathrm{erg.s}^{-1}$$

$$= 5 \times 10^{38} \frac{I}{10^{45}} \mathrm{erg.s}^{-1} \qquad \text{(Crab)}$$

The only theory used here is the theoretical number for I = moment of inertia. The spin down is explained by assuming the object has an intense magnetic field, of strength so high that at radii $\sim$ vacuum wavelength $\lambda = c/\Omega = cP/2\pi$ = 48 000 P km, the energy density in particles is still less than the total electromagnetic energy density (in most ideas, much less). At radii $r >> R$ = stellar radius, it sufficies to assume the magnetic field is given by the dipole component, which is a good description of the field out to radii $\sim \lambda$. To make a pulsar, the dipole must be inclined with the rotation axis. The torque on the star is explained by assuming sufficient current flow exists in the dipole field at $r \sim \lambda$ to induce a toroidal field $B_\phi\ (r \sim \lambda) \sim B_{dipole}\ (r \sim \lambda) \sim \mu/\lambda^3$. This requires currents of magnitude $\sim B/P$; whether they are displacement currents or conduction current does not matter. Simultaneoustly, the rotation of the magnetic field induces a poloidal electric field $E \sim (r/\lambda)\ B_{dipole} \sim \mu/\lambda^3$ at $r \sim \lambda$. Then $\underline{E} \times \underline{B}$ includes an outward poynting flux which, when summed over the sphere of radius $r \sim \lambda$, gives a total electromagnetic energy loss rate

$$\dot{E}_{Em} \sim 4\pi\ \lambda^2 \frac{c}{4\pi} (E_\theta B_\phi)_{r \sim \lambda} = c\,\frac{\mu^2}{\lambda^4} = \frac{\mu^2\,\Omega^4}{c^3} \qquad (3)$$

With the replacement $\mu^2 \to 2\,\mu^2 \sin^2 i/3$, i = angle between angular velocity and magnetic moment, (3) yields the familiar expression for vacuum dipole radiation, the only "successful" theory of pulsar spindown! In this case the current is entirely displacement current. However, the argument that led to (3) shows that all one needs are currents $\sim B/P$ and relativistic velocity of energy flow, and indeed the relativistic mhd wind models, where the currents are all conduction, of Michel (1969) and of Kennel et al. (1979) have exactly the same energy loss as in (3), to within factors of order 1. Goldreich and Julian's (1969) scenario for a charge separated wind in the aligned rotation almost certainly does not involve current of this magnitude (Jackson, 1976, 1980 ; Scharlemann et al., 1978 ; Mestel et al., 1979 ; Michel, 1980), thus making the aligned rotator an unlikely setting for understanding even basic pulsar physics. In the oblique rotator ($i >> 0°.6\ P^{-1/2}$) conduction currents of magnitude B/P are quite likely (Scharlemann et al., 1978 and below) in addition to displacement currents of comparable magnitude, thus making a complete theory of spindown quite inaccessible to detailed solution. However, the order of magnitude of μ and of the magnetospheric electric field can be estimated by equating (3) to the observed spin down energy loss.

In the case of the Crab pulsar, it is possible that the spin down proceeds in proportion to $\Omega^{3.5}$ (Groth, 1975) ; however, it is also possible that the true spindown rate $\alpha\ \Omega^4$ is masked by the random walk of $\dot{P}/P^2$ (Cordes, 1980).

The main point I want to draw from (3) is that the magnetosphere has a large scale magnetic field $B \sim 10^{12}\ (R/r)^3$ Gauss <u>and</u> a large scale electric field $E \sim 6 \times 10^8\ P^{-1}\ (R/r)^2$ V/m for $r < \lambda$; the "exact" value of course depends on the object. At distances greater than λ, the magnetic field is expected to be predominantly toroidal, with magnitude $B_\phi \sim 4\ (\mu/10^{30}\ \mathrm{G.cm^3})\ P^{-2}\ (10^5\ \mathrm{km}/r)$ G and $E \sim B$, independent of whether the out flow is a "vacuum" wave or a relativistic wind. <u>If</u> particles <u>accelerate</u> in these electric fields, relativistic energies are easily achieved. However, in the near zone $(r \sim \lambda)$, the strong magnetic field provides a two dimensional insulator by confining particles to motion along $\underline{B}$, while in the far zone $(r \sim \lambda)$, the nature of the acceleration depends on whether the electric field is like that of a vacuum wave or like that of a wind.

(b) Acceleration in strong waves

A lot of work on particle acceleration has followed the suggestion by Gunn and Ostriker (1969), who noted that one test particle injected into the wave zone of a <u>vacuum</u> magnetic rotation (where $E/B = 1$) would be accelerated to extreme relativistic energies (monoenergetic electron distributions of energy $\sim 10^{7.5}\ m_e c^2$ looked possible for Crab pulsar parameters). I only want to point out that this idea really doesn't work, once even the slightest attempt at self-consistency is made. They correctly pointed out that vacuum-like propagation of the wave requires the wave frequency = rotation frequency to exceed the effective plasma frequency. For strong waves, this requires the number density to satisfy

$$n\ (r \sim \lambda) < B\ (r \sim \lambda)/2\ Pec \sim 4\pi^3\ \mu/ec^4P^4 = 0.3\ (\mu/10^{30})P^{-4}\ \mathrm{cm}^{-3} \quad (4)$$

Physically, all that is said here is that the current nec induced in the plasma by the wave's electric field must be less than the spin-down current $\cong$ displacement current $\sim B/P$. If the inequality is reversed, one finds the sufficient conditions for mhd theory to apply (Michel, 1969). If the number density is phrased in terms of a particle loss rate, the total loss rate must be less than

$$\dot{N}_c \overset{\sim}{=} 6 \times 10^{30}\ \frac{\mu}{10^{30}\ \mathrm{G\ cm}^3}\ P^{-2}\ \mathrm{s}^{-1} \quad (5)$$

<u>if</u> the particle flux from the star covers all 4 steradians. Modern work suggests $\dot{N} >> \dot{N}_c$ for observed and observable pulsars, thus implying a hydromagnetic wind as the relevant zeroth order picture (see below). However, a particle flux of magnitude

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$$\mathcal{N} f_c = (4\pi^2 \mu/ec^3P^4)\ (cP/2\pi\ r)^2 = 10^{10}\ (\mu/10^{30}\ G.cm^3)\ x$$
$$P^{-4}\ (cP/2\pi\ r)^2\ cm^{-2}\ s^{-1} \qquad (6)$$

as Ostriker and Gunn (1969) suggested might be present. This leads to complete disruption of their mechanism. The reason is that the basic mechanism relies on the electric field of the wave to accelerate the particle to speed = c in the direction orthogonal to the propagation direction and to the wave magnetic field $\underline{B}$. Then the strong V x B force accelerates the particle in the radial direction to speed = c also, so that in the guiding center frame, the particle sees the V x B force as almost static and moves to regions of weaker acceleration (larger radius) before the force reverses. Even a little plasma (flux << f_c) thoroughly destroys this phase matching by changing the wave phase speed to velocities > c with E/B > 1 (Akhiezer and Polovin, 1956; Max and Perkins, 1971; Max, 1973). Indeed, in the extremely strong wave limit $eB/m_e c\ \Omega >> 1{,}836\ Z/A$, where Z = nucleonic charge and A = mass number, applicable to radii somewhat greater than $cP/2\pi$ but much less than the radius of the bubble blown by the star's Poynting flux, steady travelling wave solution show that the wave demands a flux = f_c and that the energy is equipartitioned between particle and field (e.g. Kennel et al., 1973; Kennel and Pellat, 1976), but that individual particle energies are far less than estimated by Gunn and Ostriker. Of course, these plane wave results implicitly assume that the star is willing to supply this flux, which may or may not be true. In fact, the local critical flux required by these solutions is proportional to field strength and therefore declines $\alpha\ r^{-1}$ in a spherical wave, while conservation of number implies average flux must decline in proportion to r^{2}, indicating that the equipartition solutions cannot be extended to spherical geometry. Recent work by Llobet (1980) indicates a lack of such maximal flux solutions in the spherical case.

While I will argue below that the total flux probably greatly exceeds f_c, we don't know this to be true in any specific case. Therefore I think a more powerful limit is set by the results of Asseo et al. (1978), who show that Non-Linear Inverse Compton (= Synchro-Compton) radiation damping in an otherwise stable strong wave would turn the wave into γ-rays in a quite short distance, even for flux << f_c. In addition, a number of powerful instabilities have been uncovered, most of which assume the plasma zero temperature but some of which include the possibility of relativistically high temperatures, which occur even when f_c << actual flux (Max and Perkins, 1972; Arons et al., 1977; Romeiras, 1979; Asseo et al., 198L) and all of which are very likely to heat the low density plasma until radiation reaction can take the energy out of the system, most likely at γ-ray energies. Since in general pulsars are far less than 100% efficient at producing γ-rays (Ogelman et al., 1976; Kanbach et al., 1977), we can fairly safely conclude that particle losses in sufficient number to make the objects interesting cosmic ray sources are not consistent with strong wave acceleration. Physically, all this happens because E/B > 1 in these waves. Then the particles always move so as to make the field approximately a pure electric field in the rest frame of the particle's oscillation center, with very large V.E work done on the particle. By contrast, in mhd winds, the guiding centers move so that E = 0 in the comoving frame, with obvious differences in the V.E work that can be done in accelerating particles, creating instabilities and radiating the energy. Since I think the particle flux from a pulsar is at least f_c and probably is >> f_c I think any correspondence between particle acceleration models which rely on strong waves and observation is purely coincidental, resulting from the fact that the gross electromagnetic energy loss rate is independent of the specific form taken by the Poynting flux. For various examples of strong wave models applied to in a variety of circumstances, see Rees, 1971, Kulsrud et al., 1972, Rees and Gunn, 1974, Arons et al., 1975, Gaffet, 1976, Weinberg, 1980 and Kundt and Krotscheck, 1980.

(c) Acceleration in large scale E_{11}

Most modern work on the pulsar itself suggests fluxes vastly exceed f_c, thus implying an mhd wind. Several distinct lines of thought suggest that above the surface of the star, along polar field lines, there are charge separated zones within which large scale parallel electric fields $E_{11} = E.B/B \neq 0$ exist, creating linear (electrostatic) accelerators and which also extract currents from the star of magnitude B/P which flow along B. The motion of the accelerated charges along B leads to the emission of γ-rays at low altitude, whose magnetic conversion leads to the formation at a dense electron-positron plasma. In all of the consistent theories so far investigated, the formation of this plasma limits the acceleration to a small fraction of the ultimate energy available.

(i) Starvation electric fields

Since neutron stars have intense gravitational fields ($g \sim 10^{14}$ cm.s^{-2}) and low surface temperatures (T* < few x 10^6 K, Giacconi, 1979), the gravitational scale height of any atmosphere is tiny, leading to an electrical vacuum above the surface (Pacini, 1967). But, the rotationally generated vacuum field includes components parallel to B whose force vastly exceeds surface gravity (Deutsch, 1955; Goldreich and Julian, 1969), leading to the electrical extraction of a charge separated plasma and (possibly) current from the star (in this respect, pulsars differ from planetary magnetospheres, whose plasmas are not supplied by electrically driven flow along B for the most part). Particle fluxes comparable to (6) are just what one requires to poison E_{11}, and one expects the extraction to continue until such poisoning occurs.

To see why this is so, consider a star whose electric field is static in the corotating frame (this includes vacuum dipole radiation), an approximation which very likely applies to many processes which occur on time scales << P (Arons, 1979) and may apply globally. Then there exists a potential Φ such that the electric field in the local Lorentz frame corotating with the star is a potential field, or

$$E + \frac{1}{c} (\Omega \times r) \times B = - \nabla \Phi \tag{7}$$

(Schiff, 1939; Mestel, 1971; Fawley et al., 1977). The interpretation of (7) is simple. At low altitude, the magnetic field is so strong that $E + c^{-1}(V \times B) = 0$ is a good approximation, where V is the velocity of any charged particle perpendicular to B. Solving for V with (7) for E yields

$$V = (\Omega \times r)_{\perp} + c \frac{B \times \nabla_{\perp} \Phi}{B^2} \tag{8}$$

If $\Phi = 0$, the particles corotate (true for the rigid crust). However, if $\nabla\Phi \neq 0$, the particles don't corotate; in this context, this is possible only if $\nabla_{/\!/} \Phi \neq 0$, since the crust is an excellent conductor. Since $\nabla_{/\!/} \Phi = - E_{/\!/}$, the lack of corotation is intimately associated with particle acceleration, and we need to ask, how big is Φ ?

To study this question, we relate electric fields to the particles through Gauss's law (Poisson equation). With (7) for E, this yields :

$$- \nabla^2 \Phi = 4\pi (\eta - \eta_R) \tag{9}$$

where η = charge density and

$$\eta_R = - \frac{\Omega \cdot B}{2 \pi c} + \text{small terms} \tag{10}$$

The potential Φ can be estimated by noting that

$$\Phi = 4\pi (\text{length})^2 (\eta - \eta_R) \tag{11}$$

with the length chosen to be the smallest in whatever geometry is considered. Of course, Φ can be calculated by the usual machinery of potential theory, if $\eta - \eta_R$ is known. The question then reduces to how much "charge separation" $\eta - \eta_R$ exists. Note that the actual plasma can be completely charge separated with $\eta = \%\eta$ as one expects if the magnetospheric charges are supplied by electric force, yet as far as acceleration and non-corotation are concerned, the rotating system acts as if it is charge neutral if the charge density exactly equal to η_R is supplied. In magnitude

$$\frac{\eta_R}{e} = 7 \times 10^{10} \frac{B(r)}{1\ \text{TG}} P^{-1} \text{cm}^{-3} \tag{12}$$

Multiplied by c, this density yields the flux f_c referred to the stellar surface along dipole field lines (flow tube area $\propto r^3$).

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The vacuum $\eta/\eta_R << 1$ yields potentials over the magnetic pole $\Phi > 10^{13}$ V; I assumed the polar cap has a radius $\sim 10^4 P^{-\frac{1}{2}}$ cm in estimating this voltage, with resulting vacuum $E_{//} \sim 10^{11}$ V/m. This Φ so vastly exceeds the gravitational binding energy that all binding seems unlikely, except in very unusual circumstances (as we will see, the unusual may be usual, in limited regions). Goldreich and Julian (1969) suggested that flow off the stellar surface continues until the match between η and η_R is excellent, so close that the residual electric field just balances gravity (in electron zones, where $\eta_R < 0$, this means $(\eta - \eta_R)/\eta_R < 10^{-9}$, typically). This results in either non relativistic flow or (more likely) no flow at all; see the references on the aligned rotator above. However, if for some reason, a zone is even a little starved of particles, electric fields much larger than the Goldreich-Julian estimate, yet smaller than vacuum fields, might occur. If such "starvation" can be maintained in a manner consistent with the processes which supply particles and relax $E_{//}$ to its "quasi-neutral" value, the resulting combination of electric field, rotational EMF and plasma is a good candidate for a relativistic particle accelerator. Note that if starvation is the basic reason for strong $E_{//}$, the essential physics is still the same as the reason for non zero $\nabla \cdot E$ in strong waves, namely, the vacuum rotational EMF is incompletely cancelled by the conducting plasma. In the near zone, approximately electrostatic fields under consideration here, the phase velocity effects which are so important to strong wave acceleration do not cause any problem, leading to some possible models which have yet to run into definitive observational or theoretical difficulties.

(ii) Discharge models

Sturrock (1970, 1971) suggested the first, electrostatic acceleration model. I will not review his scheme since when viewed from the demands of constructing a consistent acceleration theory, he vastly overestimated the electric potential available at the stellar surface, essentially because by neglecting η_R compared to η, he implicitly assumed the presence of an "anode" somewhere above the freely emitting stellar surface (= "cathode"), which could support the surface charge needed to give a net accelerating electric field when combined with the space charge of the accelerated stream (see Fawley et al., 1977 and Arons, 1979, for more comment; the model of Kennel et al., 1979, suffers from the same defect). Given his potential, Sturrock suggested a number of interesting consequences, especially copious pair creation and curvature γ-ray emission, which have survived into later work. He did not make any realistic attempt to account for the tendency of the pairs to poison this electric field, and as remarked by Arons (1979), the unsteady creation of relatively low energy pairs ($E \sim$ 1-100 GeV) in regions whose voltage drop ($e\,\Delta\Phi \sim 10$-10^3 TeV) vastly exceeds the initial energies of the secondaries almost certainly lends to very intense "auroral" bombardment of the polar cap with X-ray emission vastly in excess of past and present observations, an interesting constraint which will be of some importance below. Nevertheless, his results are still used (e.g. Sturrock and Baker, 1979). I regard his work as a fascinating and innovative piece of order of magnitude phenomenology; if one does not ask questions about the physics of the acceleration and simply accepts his estimates of particle output as given, a large number of plausible estimates of various pulsar phenomena can be generated. However, despite much propaganda to the contrary, no specific, convincing model of pulsar pulses has been constructed on his basis which covers more than a small fraction of the known facts. Since this problem plagues all models, I prefer to stick to those which are not internally contradictory, to which I now turn.

Ruderman and Sutherland (1975) proposed a model which preserves many of the features of Sturrock's yet does give a reasonable if crude account of the accelerating voltages that might be available, under one set of assumption that lead to starvation. They hypothesized that currents of magnitude B/P exist, so that the polar field lines continuously lose plasma to infinity (the polar field is assumed to be "open"). They also hypothesized that the surface has very high work function, so high that particles of the same sign as η_R cannot be extracted from the star even by the vacuum electric field. Typically, this requires the work function to exceed 5 keV. Since energies this high may be typical of the binding energy of a perfect, uniform lattice of pure cold iron immersed in a superstrong magnetic field (Ruderman, 1971; Flowers et al., 1972), Ruderman and Sutherland (= RS) hypothesized that those stars for which $\Omega.\mu < 0$ and $\eta_R > 0$ would not be able to emit charges to replace plasma flowing off to infinity. Then as plasma leaves the poles, a starvation zone is opened up (a "gap") in which $\eta = 0$ and the full vacuum potential becomes available. The polar cap size is roughly given by the area (Goldreich and Julian, 1969)

$$A_{cap} \sim 7 \times 10^8 \ P^{-1} \ (R/10 \text{ km})^3 \ \text{cm}^2 \tag{13}$$

and since the field lines are assumed to be good conductors, (11) implies the maximum potential, if the whole polar zone of volume $A_{cap}^{3/2}$ is evacuated, is

$$\Phi_{max} \cong 7 \times 10^{12} \ \frac{B}{1 \text{ TG}} \ P^{-2} \ \left(\frac{R}{10 \text{ km}}\right)^3 \ \text{Volts} \tag{14}$$

The voltage drop is about equally along and across B. This voltage is the same as that assumed to be present by Sturrock.

However, just as Sturrock pointed out, voltages of this magnitude are unstable. Any stray γ-ray that gets into the polar region (for example, from the interstellar medium), is absorbed in the magentic field and creates an $e^\pm$ pair. Once created in the vacuum zone, the $e^\pm$ accelerate to energies $> 10^{12}$ eV and radiate more γ-rays of energy ~ 1 GeV, since the $e^\pm$ move along curved field lines. The secondary γ-rays are absorbed <u>within</u> the polar cap region, thus generating more pairs in the region where $E_{\parallel} \neq 0$, more γ-rays, etc... An avalanche results, which grows at each point until a charge density $\sim \eta_R$ is created, at which point the accelerating E is assumed to be shut off. The result is a discharge composed of an outwardly moving positron beam and an inwardly moving electron beam, each of total number flux $f \sim \eta_R c/e = 2 \times 10^{21}$ (B/1TG) P^{1} cm^{-2} s^{-1}. Because the electric field is assumed to be quenched when $f \sim \eta_R$ c/e, the voltage is limited to values much below Φ_{max}. Since many discharges occur in the cap at the same time under most circumstances, they argued that the outwardly moving positron beams and further pair creation by the γ-rays emitted by the beams would keep the voltage limited in a quasi-steady manner. Then the polar gap is supposed to be like Figure 4, with $E_{\parallel} \neq 0$ on the upper surface because of the mobile pair plasma appearing at and above this point while $E_{\parallel} \neq 0$ on the stellar surface because of the strong ion binding in the crust.

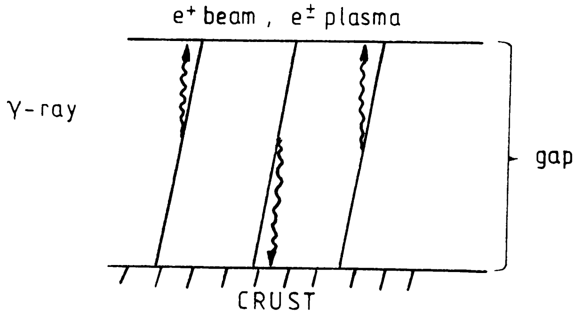

Figure 3. RS gaps

RS went on to elaborate this scheme into a complete scenario for pulsar emission, about which I have made various remarks elsewhere (Arons, 1979). The main aspect that concerns me here is whether this picture has enough energy in accelerated particles to explain γ-ray pulsars. The answer is no, if their 1-dimensional view of electric field poisoning is correct. The total J.E work done in their zone is

$$E_{RS} = 10^{30} \left(\frac{B}{1\ TG} \right)^{6/7} P^{-15/2}\ erg.s^{-1} \qquad (15)$$

Most of this energy is in the positron beam, whose energy goes mostly into creating more pairs above the gap in the case of the Crab and Vela pulsars. Then the gamma ray luminosity is less than 10% of (15) in each of these cases, while the particle luminosity (15) is already a factor of 40 below the γ-ray luminosity of the Crab pulsar and a factor of 10 below the gamma-ray luminosity of the Vela pulsar. Nevertheless, the properties of this accelerator are interesting for other reasons. The output of each polar cap, in addition to the dissipation rate (5), is a positron beam of initial energy 2 $(B/1\ TG)^{-1/2}\ P^{-1/2}$ TeV. For pulsars with large P the positron energy decays by γ-ray emission to a final energy $\sim$ 30% of its initial value at the top of the gap. The average particle loss in each beam is about N_c per polar cap, with N_c given by (5). The pair plasma created in large P cases has a flux at least $10^3 N_c$, giving a lower bound to the loss rate for the Crab pulsar $\sim 3 \times 10^{36}$ s^{-1}; another factor of $\sim$ 50 is quite likely, from synchrotron emission by the first generation of pairs and the magnetic conversion of the gamma rays. These pairs are injected into the outer magnetosphere and into the wind with relatively low energy, typically $\sim$ 100 MeV to 500 MeV (the exact value depends on the paper containing the estimate, and almost all estimates have ignored the broad momentum dispersion resulting from this injection mechanism).

A fairly strong prediction of the model is that an amount of energy equal to (15) is put into the polar cap by the downward flux of electrons and γ-rays. Here the dense stellar material easily thermalizes the energy giving rise to thermal photon emission with effective temperature

$$T_{cap}\ (RS) \cong 400 \left(\frac{B}{1\ TG}\right)^{3/21} \left(\frac{0.089}{P}\right)^{2/7} \text{eV} \tag{16}$$

and a soft (0.1 - 2 keV) X-ray flux at the earth $\sim$ 1 Uhuru count x $(500\ \text{pc/distance})^2$ for the Vela pulsar. Fluxes of this magnitude would be easily observed in the Einstein observations of Vela, since the stellar rotation would make the caps appear as a modulated source (other cases are possible too, but Vela is the most favourable). Cyclotron scattering might lead to a change in the modulation pattern, if the closed zone of the magnetosphere has a density greatly in excess of η_R/e, but is unlikely to change the photons' energy (Arons, 1979), so this prediction is a strong test of the model.

So far, such X-rays have not been observed. One possibility is that the whole idea is wrong. However, the use of the vacuum approximation is an inconsistent assumption. The reason is that the temperature (16) is high enough to lead to free thermionic emission, even from a perfect metallic surface. Other effects (impurities, lattice defects, ridges, ...) all suggest that the effective work function is lower than the calculated binding energy anyway. When ions are freely available, the charge density of the extracted ion current is very close to η_R and $\Phi \ll \Phi_{max}$ near the star, where the magnetic opacity is large, even without pairs present to poison the potential. Nevertheless, the potential may be barely large enough to allow e± discharges to occur in the midst of the ion stream (Cheng and Ruderman, 1977, Fawley et al., 1977; Jones, 1978). Because $\eta - \eta_R \ll \eta_R$ even before the discharge occurs, the electric field may be quenched with a lower flux created in the electron and positron beams and therefore less polar cap heating. Whether or not this effect is real, and whether or not the resulting scheme violates the X-ray data, is unknown; a real answer requires following the system of discharges as each enters the regime of non linear growth (see Arons, 1979), a task only addressed for a single spark in a vacuum field by Fawley's (1978, 1980) one dimensional particle-in-cell simulations.

My opinion is that these phenomena might occur in the manner outlined, as far as the internal consistency of the theory is concerned, with the question of observational tests unresolved. If these discharges do occur (with free emission of ions), the plasma density in the outer magnetosphere probably greatly exceeds η_R/e, $N >> N_c$ and the energy loss is then through an mhd wind, not a superluminous strong wave. But, the energy put into particle acceleration by these surface gaps cannot explain the high frequency emission from the Crab and Vela pulsars; the upper limit (15) to the energy available is too small.

To find this energy, the discharge theorists have turned to "outer gaps" where the same sort of spark phenomena are supposed to occur. These are regions near the null surface where $\Omega.B = 0$, on one side of which the magnetosphere demands a negative charge density, while on the other side, a positive density is required. If these particles can be supplied only by the flow along field lines from the star of a charge separated plasma, most geometries have a problem in that positive particles cannot get to the required region by flow through the negatively charged zone, and vice versa, a difficulty realized and swept under the rug by Goldreich and Julian. Holloway (1973) pointed out that the magnetosphere might form a vacuum zone near this surface, as the particles on open field lines streamed away from the star (if such streaming is allowed by the global electric field). Cheng, Ruderman and Sutherland (1976) took advantage of this idea to develop a rough discharge model at high altitude, a picture elaborated by Cheng and Ruderman (1977b) into a complete scenario for the Crab pulsar and revised by them (1980) and elaborated by Ayashli and Ogelman (1980) into a scenario for all γ-ray emitters. The basic physics is the same (except that in the 1980 paper of Cheng and Ruderman, pair creation occurs through the collision of curvature γ-rays with thermal photons from the heated polar caps, instead of magnetic, which may allow some models to produce acceptably small thermal X-ray emission). Because the opacity at high altitude is much lower than at the surface, the emission of magnetically convertible photons requires higher particle energy, larger voltages and larger J.E work done in accelerating the e+ and e- beams in the gap. The result (for the curvature emission-magnetic conversion model) is a particle acceleration luminosity

$$\dot{E}_{gap} \sim 3 \times 10^{34} \left(\frac{B_{surface}}{1\ TG}\right)^{4/5} \left(\frac{33\ msec}{P}\right)^{3/5} \text{erg.s}^{-1} \qquad (17)$$

This dissipation rate is in the right ball park, especially since the particles in the beams radiate away most of their energy as soon as they leave the gap in the short period models. However, most of these gamma rays are converted into pairs, so the models are not 100% efficient in putting energy into γ-emission, but they are

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$\sim$ 50% efficient in converting the luminosity (197) into soft X-ray emission from the polar caps. Auroral bombardment by one of the beams and its secondary plasma creates an X-ray luminosity $\sim \dot{E}_{gap}/2$ with effective temperature

$$T_{cap} \text{ (outer gap)} = 3.0 \left(\frac{B_{surface}}{1\ TG}\right)^{1/5} \left(\frac{89\ msec}{P}\right)^{3/20} \text{ keV} \quad (18)$$

An X-ray flux of this magnitude and colour would be easily observable from the nearer pulsars, including Vela. Furthermore, the energization of the cap cannot be reduced by unknown amounts by assuming the existance of a space charge limited flow of ions from some other source, as is possible in the surface gap case. Therefore, I think outer gaps in their original form are in direct conflict with X-ray observations of pulsars. In fact, I don't think outer gaps exist, since injection of dense pair plasma from the poles in either the surface gap model or the slot gap model to be outlined next would short out the electric field at the $\Omega . B = 0$ surface, and plasma circulation and radial diffusion into the closed zone (Arons, 1979; Kennel et al., 1979) can easily keep the null surface shorted out in the closed zones. In addition, there are many problems, common to all of these theories, with the ability of outer gaps to actually produce the spectrum and pulse shape of γ-ray pulses, as I'll mention below.

(iii) A steady flow theory : Slot gaps:

This theory was proposed by Arons and Scharlemann (1979) = AS, based on previous work on the acceleration problem by Fawley et al. (1977) and Scharlemann et al. (1978); see Arons (1979) and Scharlemann (1979) for qualitative discussion. My remarks here are based on the quantitative work by Arons (1980 a). It does not suffer from the problems I have described in the discharge models and does (more or less) have enough particle energy to explain γ-ray pulses, but does not, in its present level of development, produce sufficient hard photon emission that looks like a pulsar. Since it is a steady flow theory, a fairly simple quantitative expression of ideas is possible.

Like the surface discharge models, it is based on there being a starvation zone over the pole, but of a more subtle type. Consider a polar flux tube whose form is shown in Figure 4, whose sense of curvature is toward the rotation axis (this was called "favourably curved" by AS). Assume $\Omega . \mu > 0$. Then the electric field extracts electrons from the thin atmosphere at the stellar surface with $E_{/\!/} = 0$ in the atmosphere. The acceleration mechanism also applies to ion zones, but the consequences for pair creation are then quite different. Assume (as is required by the energetivs of spin down) that the polar flux tube is bounded by a region of $\Phi = 0$; this boundary condition may identify the transition field lines where return currents flow and pairs precipitate from high altitude. Finally, assume the potential is monotonic with height above the star;

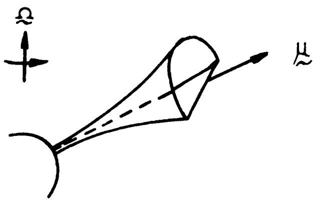

Figure 4. A favourably curved flux tube.

the opposite hypothesis, needed in Mestel et al's (1979) nonrelativistic models of the aligned rotator, very likely leads to sufficient dissipation to relax any other structure to the maximal, relativistic acceleration found here. Then the flux tube shown is a starvation zone in spite of the free availability of the electrons. The reason is that at low altitude ($r - R << cP/2\pi$) the relativistic electron flow is entirely parallel to B. Then $\eta = J_{\parallel}/c \propto (\text{Area})^{-1} \propto B$, since the polar flow tube is a magnetic flux tube. To have $E_{\parallel} = 0$ at the surface, one must have $\eta = \eta_R$ at the surface, to a high degree of accuracy. But, $\eta_R \propto \underline{\Omega}.\underline{B} \propto B \times \cos$ (angle between $\underline{\Omega}$ and $\underline{B}$) and this cosine increases with increasing altitude above the star in favourably curved flux tubes. Thus, above the surface, $\eta_R/\eta > 1$ and the tube is starved with the fractional charge separation increasing in proportion to r^2-R^2. This configuration is possible only in the oblique rotator; for this reason, my opinion is that studies of the aligned rotator are irrelevant to active pulsars.

It's easy to show that this starvation mechanism leads to large voltages fairly near the star. Since the flux tube is long and narrow, the length that enters in (11) is the local width of the tube, with the result

$$\Phi \sim 2 \times 10^{12} \frac{B}{1TG} \left(\frac{0.2\ s}{P}\right)^{5/2} \left(\frac{\text{dipole radius of curvature}}{\text{actual radius of curvature}}\right) \left(\frac{r}{R} - 1\right) V \tag{19}$$

in the region tube width << r-R << R. For detailed theory see Arons and Scharlemann (1979) and Arons (1980 a). Voltages of this magnitude cause electrons to radiate GeV γ-rays by the curvature process, just as in Sturrock and RS models, except that now the characteristic heights are more typically $\sim$ 1-2 km instead of 10-100 m. The mean free path for these γ-rays is exponentially dependent on the height of the emitting particles, in the form mfp$\propto$ exp (constant/(height)^4). Thus pairs appear abruptly, at and above a well defined surface, whose location is about where the mfp = height. The γ-rays from lower altitude electrons are almost all of lower energy, and thus create pairs above the surface (called the "pair formation front" = PFF by AS), or escape. The pair creation rate at the PFF is quite large, $\sim 10^2$ pairs km^{-1} per primary electron, and the pairs' relatively low energy and free mobility along B result in the PFF being a surface of $E_{\parallel} = 0$. This results in very few of the newly created positrons being caught in the electric field and accelerated down onto the star so that pair creation does not disrupt the starvation electric field but merely terminates it continuously at the PFF. The PFF is rather like a detonation wave in a chemically reacting flow; below it ("upstream") the polar flux tube is starved and supports a fairly strong $E_{/\!/}$ (10^{10} V/m is typical), but at the PFF, the partial vacuum "explodes", a dense pair plasma appears and travels outwards ("downstream") along with the original electron beam. The region below the bottom point on the PFF is called the "diode" zone by AS, in analogy to space charge limited relativistic diodes.

There is an additional feature to this scheme. Near the "walls" of the polar flux tube, $E_{/\!/}$ is weak and Φ is small in the high opacity region r < 2R. Then pairs are not created at the outer rim of the primary electron beam. This means the pair plasma is surrounded by a thin annular starvation zone which extends to high altitude, a "slot" as illustrated in Fig. 5. Within the unshaded region, which extends at least to radii $\sim cP/2\pi \gg R$, $E_{/\!/}$ is not shorted out and high voltages are achieved (Even though $E_{/\!/} \sim 10^6$–10^7 V/m in the center of the slot is small compared to $E \sim 10^9 - 10^{11}$ V/m typical of the center of the diode, the much larger length along field lines allows the voltage to accumulate). The minimum model for particle acceleration is then diode + slot region, assuming no further energy is generated within the pair plasma or at the boundary layer between the slot and the pair plasma (the dynamics of the PFF were studied by AS, who showed this thin layer contributes miniscule dissipation and also allows the plasma to adjust to $E_{/\!/} = 0$ with only $\sim 10^{-4}$ positrons being accelerated toward the star for each primary electron accelerated away from the star). The total luminosity in particle acceleration depends on the volume of the diode + slot, which is found by solving the appropriate nonlinear free boundary problem (Arons, 1980 a). The result for the total J•E work on the electron beam in the diode + slot can be put in the form

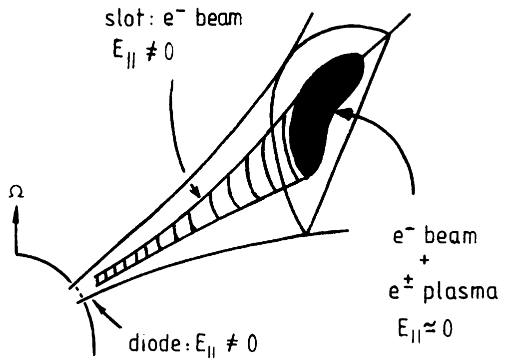

Figure 5. Diode + slot model of starvation zone.

$$L_P = \sim \frac{\mu^2 \Omega^4}{c^3} \left[1.5 \times 10^{-2} P^{-1/2} E_D (P/P_D) + E_S (P/P_D) \right] \qquad (20)$$

where P_D = period when the opacity and voltage are just sufficient for the creation of one pair per primary e- along the central field line of the flux tube, with $P_D \sim 0^s.3$–3^s the typical values depending precisely upon B(R), R and the radius of curvature of the surface magnetic field (the exact expression is given by Arons, 1980a). Since $\mu^2 . \Omega^4/c^3$ is the spin down luminosity, $1.5 \times 10^{-2} P^{-1/2} E_D$ and E_S are the efficiency of conversion of spindown energy lost into an accelerated electron beam in the diode and slot regions respectively, with

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$$E_D \cong 0.09 \left(\frac{P}{P_D}\right)^{2.24} \tag{21}$$

and

$$E_S = 0.5 \left(\frac{P}{P_D}\right)^{5.08} , \tag{22}$$

The properties of the e± plasma are straight forward consequences of the generation scheme. I find (Arons, 1980 b) $\gtrsim 10^3$ pairs per primary beam particle (for an object like the Crab, the number is more like 5×10^4) with a broad dispersion momenta parallel to B on most field lines of the plasma flow tube, in the range $\sim$ 10 MeV/c to $\sim$ 1 GeV/c. The primary electron beam on field lines that cross the PFF puts most of its energy into creating pair plasma in pulsars with large $\dot{P}$, while in those with small $\dot{P}$ or long P, the beam escapes to high altitude with most of its energy intact. In either case, the total energy put into this part of the beam is given by the first part of (20), and the energy per beam particle at the PFF is $\sim$ 3 TeV to 10 TeV, depending on the exact location. In the slot, acceleration continues to higher energy, with the exact asymptotic final energy unknown because it depends on the unknown structure of the outer magnetosphere and on other high altitude physics (expression 20 is calculated assuming acceleration continues out to r $\sim$ cP/2 in a dipole field, where it ceases). In total, the beam has a flux f_C. Therefore, when $P/P_D < 1$, this model, like the RS picture, puts out a plasma with total flux $\gg f_c$, indicating spindown is basically by an mhd wind. The presence of special low density zones should not be ignored, however.

Application of (20) to Vela shows that more than enough $\underline{J}.\underline{E}$ work is done in the model to explain this pulsar's γ-rays, while for the Crab (20) can be adjusted to be within 1/2 of the required γ-ray luminosity. This is encouraging, since (20) is a minimum to the work done (see below), and in principle particle energies can be radiation reaction limited so that 100% of the J.E work goes into radiation (just as stars put essentially 100% of their nuclear energy generation into radiation). However, in the specific application of the pure slot gap model to pure curvature emission from the Crab and Vela, I find such radiative efficiency is not so; in both cases, $L_\gamma/L_p < 0.1$. For this acceleration model, this negative result is a good thing. Just as in all other curvature emission theories with more or less monoenergetic beams as the γ-ray emitters at each altitude, the γ-ray spectrum is too flat (cf. Massaro and Salvati, 1979, and Hayvaerts and Signore, 1980, for general phenomenological studies). Also, as in other curvature emission theories so far proposed, there is insufficient localization of the source to give a sharp pulse. Unlike other models, the slot gap theory does localize the acceleration at high altitude and its emission to a thin sheaf of field lines, but since the field lines diverge with curvature, an observer sees beamed radiation from different altitudes at different rotational longitudes, giving a broad pulse (see § II above). These diseases are typical of all models employing laminar acceleration and pure curvature emission, starting with Sturrock's and ending with the model described here.

Despite my obvious prejudice, I think the diode + slot gap scheme is capable of overcoming its present problems. It has a number of attractive features. It produces an interestingly large total acceleration energy at high altitude without having manifest internal contradictions and without creating thermal emission from the poles in excess of current observations (see AS for the minimal estimates). The relatively large total acceleration is produced with localization of the acceleration zone to a thin sheaf of polar flux surfaces, which is 1/2 of the localization needed to make a successful model of pulses in the higher energy photons. It automatically yields a single pole scheme, since an observer oriented at random with respect to the rotation axis can see outflow and resulting beamed radiation from the favourably curved part of only one polar flux tube. Even if the magnetic field is completely symmetric, the observer's line of sight looks into unfavourably curved regions when the star rotates by 180° (see Fig. 11 of Arons, 1979), a zone where strong outward acceleration, pair creation and (presumably) beamed photon emission do not occur. Another, new argument in favour of this scheme is that such single pole models may explain the gross assymetry in the excitation of the Crab nebula evident in the HEAO-B images of the nebula. If one pole of the star has magnetic structure like that of figure 4, while the other pole is much less able to create outflow and pairs (as can be true for example, in the dipole + axisymetric quadrupole model of Barndard and Arons (1980) when the magnetic axes are aligned with each other but not aligned with the rotation axis; see Fig. 7 of Arons, 1979), the composition of the stellar wind is grossly asymmetric with respect to the rotational equator, with much larger particle flux in one hemisphere. This is probably what is needed to understand the morphology of the nebular emission, if, for example, the acceleration behind the nebular X-ray emission occurs in a shock wave as the wind collides with the inner edge of the nebula (see below), and is likely only if the pulse-interpulse morphology of the stellar emission arises in a single pole, as is possible in the slot gap scheme.

The basic problems in the current form of this model are (1) its lack of radial localization of high energy emission, (2) a mild lack of total energy for application to the Crab, (3) the inapplicability of curvature γ-ray spectra from essentially monoenergetic beams to the observed data, and (4) the inability of laminar, ultrarelativistic flow of an electron beam along curved field lines to create high brightness temperature radioemission. All of these problems are traceable to the ideal conductor approximation used to represent the boundary between the slot gap and the pair plasma. This is a good approximation at low altitude, but becomes poor at large radii where

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relative streaming between the plasma components in the much weaker magnetic field may give sufficient collisionless dissipation to enhance the acceleration efficiency and create collective radio emission (I favour the electromagnetic form of the E x B shear flow instability described by Arons and Smith (1978), but this is by no means the only possibility). More efficient emission of high energy photons by the synchrotron process may occur from excitation of pairs in the boundary layer to finite Larmor orbits by the relevant form of a beam cyclotron instability. Because of the finite threshold for this type of instability, radial localization of the synchrotron emission becomes possible, in addition to the angular localization already imposed by the pair creation model of the boundary layer.

It is not known now whether these effects are sufficient to give an explanation of the photon data, within the context of the consistent dynamical model outlined above. However, recently Machabelli and Usov (1980) have shown how some aspects of such effects might lead to an interesting model of high frequency emission from pulsars. They adopted Tademaru's (1973) elaboration of Sturrock's high voltage scheme and show the highest energy plasma component in Tademaru's model has a resonant beam cyclotron instability at radii $\sim cP/2$, when applied to the Crab pulsar. They use quasi-linear theory to argue that the resulting acceleration of the pairs into finite gyrational states might give rise to X-ray and γ-ray synchrotron emission with a spectrum like that observed. They are unable to reproduce the optical spectrum, nor, given the lack of angular localization in their emission region, can they get a sharp pulse (they do have some radial localization of the emission because of the finite threshold of the instability). As basic theory of particle acceleration, this model is still plagued with the problem recognized by Tademaru in his particle acceleration paper, namely, that the creation of the dense pair plasma is not consistent with the high voltage assumed at the polar cap. Nevertheless, if viewed as a semi-phenomenological model of photon emission, I think Machabelli and Usov's work reveals the kinds of effects needed in order to make a successful theory.

IV - COSMIC RAYS

Cosmic rays are basically a spectrum of relativistic nuclei. The models I have outlined produce mainly pairs. Therefore, one may well ask, what do pulsars have to do with cosmic rays?

(a) Pairs and positrons

Both surface gap and slot gap + diode models, when applied to an object like the Crab pulsar, produce a minimum of a few x 10^{36} electron-positron pairs/sec. In addition, further pairs are produced by the synchrotron photons emitted by preceding generations of pairs can enhance this number by another factor $\sim$ 50-100 in the slot gap + diode case (Arons, 1980 b); this is probably true in the surface gap case also, but I haven't studied this. The work of Alber et al. (1975) suggests that the Sturrock-Tademaru view has similar results, when done with some attention to consistency.

These rates of particle supply are sufficient to explain the Crab nebula (where the density is too low to yield a 511 keV annihilation line), but further acceleration beyond that supplied by the starvation zones in either model is needed to explain the energetics of the nebular X-ray emission (see (15) and (20). It is obvious that the composition of these model pulsars' output is nothing like the observed cosmic ray source spectrum (cf. Cassé, 1979). Therefore, the only role observed pulsars might play as direct cosmic ray sources is in providing positrons and electrons.

To estimate the significance of this possibility, I assume the number of pairs created per primary beam particle is a constant $\sim 10^{+3}$, independent of magnetic field and P (in fact, it is a function of P/P_D, but I stick to simple estimates here). I also assume the angular momentum loss is given by (3). Then the total number of pairs ejected by a pulsar is

$$N_{\pm} = \chi \frac{Ic^2}{e} \ln (T/\tau) = 10^{49} \frac{\chi}{10^3} \frac{I}{10^{45}\ g.cm^2} \frac{10^{30}\ G.cm^3}{\mu} \frac{\ln (T/\tau)}{7} \quad (23)$$

where T = pulsar lifetime (= time to cessation of pair creation?). $\sim 10^6$ y (Gunn and Ostriker, 1970; Fujimura and Kennel, 1980 ; Barnard and Arons, 1980), τ = initial spindown time = $Ic^3/\mu^2\Omega_i^2$, Ω_i = initial angular frequency. Assume the pulsar birthrate is $R_p \sim 10^{-10}\ pc^{-2}yr^{-1}$ (corresponding to $\sim$ 1/25 yr in a galactic disk of radius 10 kpc, roughly in accord with Taylor and Manchester's (1977) birthrate), while the confinement time is $\tau_{CR} \sim 2 \times 10^7$ y in a cosmic ray disk of scale height $H_{CR} \sim 500$ pc (Cesarsky, 1980). Then the total isotropic flux of electron-positron pairs one expects in the solar neighbourhood is

$$J_{\pm} \cong 32 \frac{N_{\pm}}{10^{49}} \frac{R_p}{10^{-10}\ pc^{-2}\ Y^{-1}} \frac{\tau_{CR}}{2 \times 10^7 y} \frac{500\ pc}{H_{CR}}\ m^{-2}\ ster^{-1}\ s^{-1} \quad (24)$$

If no further acceleration of the pairs occurs after they are created, the particles in the total flux (24) all have energy << 1 GeV, because of adiabatic losses in the expanding wind. On the other hand, most of each pulsar's rotational energy loss goes into the wind; only a small fraction is used creating the pairs. Then further acceleration as the winds encounter their surroundings could reaccelerate the pairs (see below). Since the observed positron flux at energies $\gtrsim$ 1 GeV is about a factor of 5 below the total flux (24) (Fanselow et al., 1969; Buffington et al., 1975; Golden et al., 1979), the observed positron flux might yield a useful constraint on the abilities of pulsars and their environs to accelerate particles, although I think a lot more will be learned by understanding the accelerator in the Crab nebula.

The flux (24) might have interesting implications for interstellar γ-ray emission. Suppose cosmic ray particles diffuse into molecular clouds with a very short mean free path. Then all of the positrons in the flux (24) incident on the cloud surface annihilate, giving rise to a maximum 511 keV line flux at the earth

$$f_{511} = 2\pi J_{\pm} \left(\frac{R}{D}\right)^2 \sim 2 \times 10^{-6} \frac{N_{\pm}}{10^{49}} \frac{R_P}{10^{-10}} \frac{\tau_{CR}}{10^{7.3}} \frac{500}{H_{CR}} \left(\frac{R}{10\ \mathrm{pc}}\right)^2 \left(\frac{1\ \mathrm{kpc}}{D}\right)^2 \quad \mathrm{cm}^{-2}.\mathrm{s}^{-1} \qquad (25)$$

for each cloud of size $R \sim 10$ pc and distance $D \sim 10$ kpc. Such fluxes are too small to observe now but may be accessible with the GRO. However, very small diffusion mean free paths are thought to be unlikely and are excluded if cosmic ray ionization is the source of the free electrons in molecular clouds (Cesarsky and Völk, 1979). If the positrons stream freely through the clouds, the expected annihilation line from the flux (24) is many orders of magnitude smaller than (25), since the clouds have insufficient (by $\sim 10^4$) grammage to slow the positrons to nonrelativistic velocity. In special place however, where R_ρ is high, the pulsars might all spin rapidly and if the total density is high, annihilation might lead to currently observable line emission for which the obvious candidate is the 511 keV line from the galactic center (Leventhal et al., 1979). See Bussard et al. (1979) for an analysis of the emission and various possible positron sources. I only point out here that pulsars are a good source, since they are prone to make pairs without making relativistic nuclei, thus avoiding some energy problems pointed out by Audouze et al. (1980). Sturrock and Baker (1979) have claimed that only Sturrock's model produces enough pairs per pulsar. I don't agree but further discussion of this point depends on better modelling and is left for elsewhere.

(b) Nuclei

In the surface gap scenarios, which allow free ion emission, some ions are accelerated outwards. However, the number accelerated is too small (by ~ 6 orders of magnitude), the energy spectrum in the models is monoenergetic, not a power law, and the composition of the ion beam is usually said to be pure iron. This last statement probably is not true, since the top ~ 100 g.cm^{-2} of the neutron star's crust is exposed to continuous bombardment by TeV electrons and GeV γ-rays, with the result that the accelerated beam could contain a whole spectrum of the spallation products of iron. However, I see no possibility for the composition that results from grinding up iron being a decent model for cosmic rays.

(c) Energetics

All theories of particle acceleration and pair creation developed so far make use of only a small fraction of the electromagnetic energy loss (3); see (20) for the most explicit example. While the particles supplied by the pulsar itself cannot be the cosmic rays, in these models, the unused energy might be reprocessed by the surroundings where the composition is more normal into a more acceptable spectrum of particles. This sort of "planetary nebula" idea was first suggested by Kulsrud, Ostriker and Gunn (1972), who used strong vacuum waves to calculate particle spectra, an approximation forbidden by modern models. However, the general idea might be OK, if the pulsars have enough energy.

If the relativistic energy loss rate applies all the way back to time 0, the Crab pulsar initially had $\sim 4 \times 10^{49}$ ergs of rotational energy. This is too small, by about one order of magnitude, to explain cosmic rays, assuming the birthrate = supernova rate, 100% efficiency of converting rotational energy into cosmic rays in the initial spindown, and all pulsars started out like the Crab. Note that this is a semi-theoretical argument; one has to use the relativistic spin down rule of thumb (3) right back to the beginning.

For other pulsars, we have no knowledge of the age in specific cases, therefore we don't know how to integrate (3). Furthermore, $P/\dot{P}$ ages don't tell us much, since the presence of too many short period pulsars with small $\dot{P}$ clearly shows that $\dot{P}$ is not a simple function of P; pulsars are not all on the same evolutionary track. The large space motions and small scale height of pulsars does show that the true age of the population does not exceed a few x 10^6 years (cf. Manchester and Taylor, 1977, for a review of this topic).

The loss rate (3) is then <u>consistent</u> with large initial angular velocities (e.g., P = 5 msec initially implies 2×10^{51} ergs of rotational energy), but there is no way to infer a specific value of the initial energy. Thus, all one can say is that the pulsars <u>might</u> have energy; whether they do is an open question.

If one accepts the hypothesis that they do, one still has to face the mechanisms by which the particles are accelerated. For reasons outlined above, I doubt that strong waves are present. Instead, one has to deal with acceleration of nucleons at the boundary of the wind from the pulsar. If the wind passes through the fast mode critical points, it must decelerate through a shock wave as it collides with the surrounding nebula/interstellar medium (Rees and Gunn , 1979, discuss this possibility in their mixed model). Such an interior relativistic shock in the electron-positron flow may be an excellent model for the excitation region of the Crab nebula (the "wisps"), especially since the single pole model outlined in the last paragraph may explain the gross asymmetry of the energy injection into the nebula. However, it is obviously not a good site for accelerating nucleons, since none is in the flow from the pulsar. If the pulsar drives the supernova (Ostriker and Gunn, 1972; Bodenheimer and Ostriker, 1975; Gaffet, 1976), the exterior shock of the supernova remnant might accelerate particles in the now quite popular scenario of Axford et al., 1977; Bell, 1978 and Blandford and Ostriker, 1978. Here, it makes no difference if the energy source is neutron star rotation (currently unfashionable) or neutron star "bounce" (currently fashionable), since the particle acceleration has nothing to do with the pulsar as such. A final possibility is at the tangential discontinuity separating the shocked wind from the pulsar from the surroundings (be it supernova envelope or shocked interstellar medium). Because the shocked wind stores much of its energy in the magnetic field, dissipation of the magnetic field in the boundary layer might accelerate the nuclei without running into energetic difficulties. If the subsequent adiabatic losses are not too severe, this environment might be a cosmic ray source peculiar to pulsars. In general, however, I doubt that there is sufficient magnetic energy storage to make this idea viable.

My opinion is that pulsars might have a lot to do with the emission from non thermal photon sources, especially the "filled" supernova remnants (cf. Caswell, 1979), and with some aspects of the γ-ray astronomy of the interstellar medium as well being fascinating objects in their own right. If the pair creation models are even vaguely on the right track (and I think they are), however, I doubt these schemes have much to do with cosmic ray nuclei.

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