EVOLUTION AND RADIATION IN PULSAR POLAR CAP MODELS[†]

M. Ruderman
Department of Physics, Columbia University

ABSTRACT

Positively charged particle emission from pulsar polar caps evolves through many stages as the cap temperature cools. In "infant" pulsars, stripped Fe ions interact with secondary $e^{\pm}$ from a 10^{12} V discharge maintained just above the cap to give coherent radio emission at very high frequencies in a very broad beam. In "adolescent" pulsars such as the Crab and Vela, lower energy Fe ions interact with streams of protons produced in the surface by photonuclear reactions to give lower frequency highly linearly polarized radiation. There is no cap $e^{\pm}$ discharge. In mature "adult" pulsars proton and/or Fe ion streams from discharge heated patches on the polar cap interact with a relativistic $e^{\pm}$ plasma to give coherent radio subpulse beams which can drift, have strong submillisecond modulations, and orthogonal polarization mode switching. Young pulsars, and some older ones, can support additional more energetic $e^{\pm}$ discharges on some open field lines in the outer magnetosphere. These all give strong double beams of GeV γ-rays and weaker γ-ray beams above $\sim 10^{12}$ eV. With Crab pulsar parameters an $e^{\pm}$ plasma associated with such a discharge also can give optical and X-ray double beams. If illuminated by the normal pulsar beam (precursor) coherent inverse Compton scattering also contributes a double beam of harder radio frequencies.

1. RADIO EMISSION AND POLAR CAP EVOLUTION

Polar cap models (PCM's) are based upon the presumption that large currents flow from the polar caps of spinning magnetized neutron stars, and move along "open" field lines through the magnetosphere into the region near the "light cylinder" where corotation must fail. In this section we consider the near cap potential drops which accelerate outflowing (positively) charged particles, the composition of these particles, the interactions among particle beams which should initiate charge bunching in the near magnetosphere, and some of the expected properties of the radiation beams these will generate. All of the

W. Sieber and R. Wielebinski (eds.), Pulsars, 87–98.

above will vary during the life of a pulsar. The rich varieties of double beamed microwave and high energy radiation which can originate in the outer magnetosphere of "adolescent" pulsars is considered in Section 2.

1.1 Magnetosphere Currents and Polar Cap Potentials

In a magnetospheric model which, in first approximation, has plasma and thus $\underset{\sim}{E} \cdot \underset{\sim}{B} \sim 0$ almost everywhere, the near magnetosphere co-rotates with angular frequency Ω and has a charge density

$$\rho_0 \sim -\underset{\sim}{\Omega} \cdot \underset{\sim}{B} / 2\pi c \,. \qquad (1)$$

PCM's assume that the current flow in the magnetosphere along the open field lines to the light cylinder is characteristically $j \sim \rho_0 c \underset{\sim}{\hat{B}}$. For a positively charged magnetosphere above the polar cap, positive charged particles would be expected to flow to the light cylinder along upward curving field lines through region (1) of Fig. 1. A return current might consist of an inflow of positive particles through region (2) or involve an outflow of electrons from the negatively charged region (3). The potential drop between open field lines which drives these currents is $\Delta V \sim 10^{13} B_{12} P^{-2}$ where B_{12} is the surface dipole field in units of 10^{12} G. The necessity for accelerating potentials in negatively charged PCM magnetospheres and possible consequences is discussed by Arons (1980). We consider first only consequences of positively charged ion outflow of magnitude $j \sim \rho_0 c$ from a polar cap and the rich variety of pulsar-like phenomena that seem to result from them. (It may well be that both signs of $\underset{\sim}{\Omega} \cdot \underset{\sim}{B}$ can lead to pulsars.)

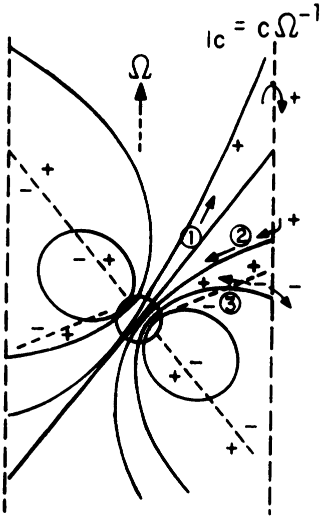

Fig. 1: Assumed Magnetosphere Current Flow

A failure of $\underset{\sim}{E} \cdot \underset{\sim}{B} = 0$ just above a polar cap and a large potential drop ΔV along open field lines can come from two sources. Because of the inertia of ions of atomic weight A and charge Ze a large $\underset{\sim}{E} \cdot \underset{\sim}{\hat{B}}$ contributes a space charge potential drop (Michel 1974, Cheng and Ruderman 1977, CR)

$$\Delta V_A \sim 4 \cdot 10^{11} \; P^{-1} \; (A/2Z)^{1/2} \; B_{12}^{1/2} \text{ volts} \,. \qquad (2)$$

When ions are bound by the relatively cool polar cap surface of older pulsars (Ruderman and Sutherland 1975, RS)

$$\Delta V_B \sim 10^{13} \; P^{-2} \; B_{12} \text{ volts} \,. \qquad (3)$$

In either case the large ΔV can be shorted out if a sufficiently strong source of e^- above the surface terminates $\underset{\sim}{E}\cdot\underset{\sim}{\hat{B}}$ before the ΔV of Eq (2) or (3) is achieved. There are two important sources for such electrons. An electron-positron discharge will create such e^- when (Sturrock 1971, RS 1975)

$$\Delta V_{\pm} \sim 10^{12}\ B_{12}^{-1/7}\ s_6^{4/7}\ P^{-1/7}\ \text{volts} \tag{4a}$$

$$\sim 10^{13}\ B_{12}^{-1/7}\ P^{1/7}\ \text{volts}\ , \tag{4b}$$

where s is the local curvature radius of $\underset{\sim}{B}$ and Eq (4b) assumes $\underset{\sim}{B}$ is pure dipole. A second source for e^- exists when ions leaving the surface region are not fully stripped of their electrons because the "cool" cap does not supply a sufficient number of the high energy photons (> 10 keV) needed to photoeject the most tightly bound electrons. Only when the ions are accelerated to very relativistic energies does an ion see enough energetic photons in its own rest frame to complete the electron stripping (Jones 1980). The needed potential drop depends on the required Lorentz factor γ; typically $\gamma \sim 10$, and the needed potential drop is

$$\Delta V_e \sim \gamma(A/Z)\ 10^9\ \text{volts}\ . \tag{5}$$

1.2 Polar Cap Surface Composition

A current flow $j \sim \rho_0 c$ from a polar cap excavates of order $\sim 10^{-2}$ P^{-1} g cm^{-2} s^{-1} of polar cap, or a total of 10^{12} B_{12} P g cm^{-2} for an initially fast pulsar which has spun down to a period P. As long as the hole is continually filled from below (the strong B retards lateral flow), where once hot (> 10^9 K) matter above about 10^8 g cm^{-3} must certainly be pure Fe, pulsars older than the Crab should have Fe polar cap surfaces no matter what the initial composition of any thin surface layer (cf. Michel 1975). But any backflow onto the polar cap of very relativistic electrons such as those which must accompany the electron production leading to Eq (4) or Eq (5) will produce protons in the very thin layer, of order 10^2 g cm^{-2} thick, just below the stellar surface. An incoming multi-GeV e^- makes a $\gamma + e^+ + e^-$ shower in matter. Giant resonance absorption of 15 - 30 MeV γ's by Fe nuclei yield p with about 1/3 the abundance of n. Jones (1978) estimates a production ratio p/e^- $\sim$ .03 per GeV of the incident e^-. This substantial production of surface layer protons plays a crucial role in this class of PCM's for the radio emission of the Crab and Vela and perhaps other pulsars.

1.3 Evolution of Polar Cap Particle Streams

As a neutron star ages, its polar cap will evolve through various stages in which the polar cap potential drop generation, the origin of the electrons which terminate it, the kinds of relativistic particle beams which move out from the cap region into the magnetosphere, and the region from which coherent radio emission comes will all vary. It is crucial, however, that at each stage more than one kind of relativistic stream is emitted at least one of which has very small energy spreads. In the beginning the evolution is governed solely by the natural cooling of the star which determines the polar cap temperature. Finally self heating processes stabilize the cap temperature (probably the present state of most pulsars) until stellar rotation becomes so slow that the star is no longer a pulsar. The expected stages in the life of a pulsar are as follows:

Infant: Polar cap temperature $T_{pc} > 10^9$ K

Such pulsars are very much younger than the Crab. The particle outflow is mainly in completely stripped Fe ions ($j_{Fe} \sim 10^3$ A cm^{-2}) accelerated through $\Delta V \sim 10^{12}$ V from inertial space effects limited by a Sturrock $e^{\pm}$ discharge. 10^{12} V positrons (j_+) carry 10^{-3} the current of the Fe ions and also give a large lower energy $e^{\pm}$ plasma above the accelerating region (RS 1975). Protons from the surface carry $j_p \sim j_{Fe}/15$. The electron backflow to the surface from the discharge could only stabilize the cap temperature at $T \sim 3 \cdot 10^5 P^{-1/4}$ (K).

Adolescent: $5 \cdot 10^6 \text{ K} < T_{pc} < 5 \cdot 10^5$ K (50 eV)

These stars range from those younger than the Crab to pulsars $10^4 - 10^5$ years old. According to Jones (1980) Fe ions do not leave the high charge density region overlaying the polar cap in a fully ionized state. Only when they achieve a Lorentz $\gamma \sim 10$ well above that region do the ions see enough X-rays with sufficient energy in their own rest frames (10 - 20 keV) to complete the ionization. These photoejected electrons return with energies in excess of 10^{10} eV and give rise to shower produced protons when they hit the surface. From a young adolescent the beams ultimately injected into the magnetosphere are j_{Fe} of completely stripped Fe ions and protons with $j_p \sim j_{Fe}/15$. Both are accelerated to about $2 \cdot 10^{10}$ V and so have $\gamma \sim 10$ and 20 respectively. There is no e^+ beam and $e^{\pm}$ discharge. An older adolescent with an even cooler polar cap will never achieve complete stripping of the emitted ions. This is because of the drop in the number of polar cap X-rays (proportional to T^3) to $n_x \sim \lambda^{-3} \sim 10^{17}$ cm^{-3}, coupled with the very small photoionization cross-section of ions in a superstrong magnetic field when the photon electric vector is perpendicular to $\underset{\sim}{B}$. Such photons, because their optical depth for interaction in the surface material is $(eB/mc\ \omega)^2 \sim 10^6$ times greater than that for photons with electric polarization parallel to $\underset{\sim}{B}$, are the main contributors to the radiated flux above the polar cap. Their photoelectric ionization cross-section is reduced by a factor $\sim c e^3 m^2 B^{-1} \hbar^{-3} \sim 10^{-3} B_{12}^{-1}$. In addition the atoms are much smaller and have more tightly bound electrons than the same atoms in $\underset{\sim}{B} = 0$. Typical photoionization cross-sections are $\lesssim 10^{-23}$ cm^{-2}. An old adolescent pulsar has $T_{pc} \sim 5 \cdot 10^5$ K (50 eV), a j_{Fe} of Fe^{++} ions only, $j_p \sim 2\ j_{Fe}{}^{++}$, and a potential drop $\Delta V \sim 10^{11}$ V. Further cooling leaves the initial Fe^+ ions unable to contribute enough photoelectrons above the gap to terminate the space-charge electric field. The pulsar is now an adult.

Adult: $T_{pc} \lesssim 4 \cdot 10^5$ K (age $\gtrsim 10^5 - 10^6$ yrs)

If the space charge potential drop from singly ionized Fe^+ ($\Delta V \sim 2 \cdot 10^{12}\ P^{-1}\ B_{12}^{1/2}$ V) still exceeds that of Eq (4), e^- from an $e^\pm$ discharge will again terminate the cap electric field as in the infant stage (this is then an "immature adult"). The j_{Fe} is carried by Fe^+, $j_p \sim 2\ j_{Fe^+}$, the positron $j_+ \sim j_{Fe^+}/20$, and the polar cap accelerating potential drop $\Delta V \sim 10^{12}$ V. But this is expected to be a temporary stage because P will increase and the near surface currents, which can contribute a relatively small curvature radius to $\underset{\sim}{B}$, will be dissipated by crust resistance. Finally the "mature adult" phase, characteristic of most pulsars, is achieved as the surface cools to a temperature so low that thermionic emission of ions can no longer supply the current carried away through the magnetosphere. Then the charge deficiency above the cap will grow until ΔV of Eq (4) is reached so that an $e^\pm$ shower is sustained with enough high energy ($\sim 10^{12}$ eV) e^- flowing back onto the surface to keep sections of it hot enough to release Fe^+ and/or the protons made by the shower initiated by these e^- below the surface (CR 1980a, Ruderman 1980, R). This can be a stable thermostatically regulated gap discharge or may oscillate in strength on a submillisecond time scale (Cheng 1981). An additional on-off quasiperiodicity, $\Delta t \sim 10^{-3}\ P^{1/2}$ s, comes from the motion of the $e^\pm$ discharge along the curvature plane of $\underset{\sim}{B}$ until it is extinguished on the cap boundary or a region of zero curvature. Reignition is accomplished by $e^\pm$ pair creation in the Coulomb field of a $\gtrsim 10^{12}$ eV proton from the e^- heated surface patch by a $\sim$ keV photon from the patch. The beams from the thermostatically regulated polar cap are mainly Fe^+ and p, with the relative amounts depending upon the relative binding (E_B) energy of both ions in the surface, and a 10^{12} eV positron current $j_+ \sim 10^{-3}\ (E_B/\mathrm{keV})^4\ j$. The cap hot patch stabilization temperature $kT \sim E_B/30$. Because of $\underset{\sim}{E} \times \underset{\sim}{B}$ drift of all e^+ and e^- in the accelerating zone above the cap, the heated patch, the patch itself, the ions, the outgoing e^+, and the secondary $e^\pm$ plasma drift around the polar cap with a period P_3 of order $6B_{12}\ P^{-1}$. It is only in this mature adult phase that (e^-) backflow determines the new position of particle injection into the magnetosphere and thus only in this phase is subpulse drifting expected.

Disceased

Finally, as P continues to increase, the pulsar can no longer achieve the potential drop needed to sustain an $e^\pm$ discharge. The pulsar will then turn off when $P \gtrsim (10\ B_{12})^{1/2}$ s.

1.4 Expected Properties of Radio Beams

A "cold" relativistic stream of ions is emitted from the polar cap surface at each age until pulsar death. In addition there are other relativistic streams, viz. another cold ion stream for adolescent pulsars, secondary $e^\pm$ plasmas for infant and mature pulsars, through which the cold ion stream flows. All such relative flows are unstable against charge bunching with a characteristic frequency equal to the relativistic plasma frequency of the dominant plasma. Such bunching will give coherent radio emission from charge acceleration along $\underset{\sim}{B}$, associated with the bunch formation itself, and, when the Lorentz factor γ of the flow is appropriate, from curvature acceleration of bunches perpendicular to the curved constraining B field. The intensity of the coherent radio emission that comes from this complex strongly interacting region of multiple streams, electromagnetic waves and current B is difficult to calculate (Pellat et al. 1981) and we shall assume only that the radio frequency is that of the relevant bunched plasmas.

Infant Pulsars: The two relevant streams are fully stripped Fe (with perhaps some He^{++}) and the secondary $e^{\pm}$ plasma. The expected coherent radiation frequency $\nu \sim 10^{12}\,(R/r)^{3/2}$ Hz (R is the stellar radius) is in excess of 10^{10} Hz. The radio beam would be exceptionally broad.

Young Adolescent Pulsars: The beams are fully (or partially, for older adolescents) stripped Fe and protons with $\gamma \sim 10$. The emitted $\nu \sim 7 \cdot 10^{8}\,(R/r)^{3/2}$ Hz is less than 700 MHz and becomes much broader with decreasing ν. The two-stream instability bunching is very strong with an e-folding distance $\ell \sim 3 \cdot 10^{3}\,(r/R)^{3/2}$ cm. For Crab parameters a broad RF beam may remain intense to of order $r \sim 10^{8}$ cm where $\nu \sim 1$ MHz. The energy of relative streaming between the two ion streams which would limit the total radiated coherent RF is initially 10^{31} erg s^{-1}. The beam γ's are too small for RF curvature radiation so that only acceleration parallel to B couples to emitted radiation. "Adiabatic walking" can then give 100% linear polarization (CR 1979). I would propose the Crab precursor pulse and the Vela RF pulse as candidates for such radiation from young adolescents.

Mature Adult: The strongly interacting streams are now protons (or partially ionized Fe) and the secondary $e^{\pm}$ plasma. The emitted coherent radiation from longitudinal and/or curvature acceleration of charge bunches has $\nu \sim 10^{9}\,(r_7)^{3/2}\,(E_B/\mathrm{keV})^{2}$ Hz and will not be inconsistent with the analyses of Cordes (1981) and others if $E_B \lesssim 0.5$ keV. The contribution from the two orthogonal accelerations gives, after adiabatic walking, incoherently mixed orthogonal modes and the possibility of sudden switching of polarization to that of the dominant one (CR 1979). Since the radiation beam is emitted from the ion-$e^{\pm}$ stream, subpulse drifting on the time scale discussed above is expected as are two independent strong submillisecond beam modulations. A variety of other model properties also seem suggestive of those of pulsar radiation beams (CR 1980a, R 1980) and I would propose this stage of a pulsar to be that in which almost all except the younger ones may be found now.

2. OTHER RADIATION MECHANISMS FOR ADOLESCENT PULSARS: ORIGIN OF DOUBLE BEAMS OF RF, OPTICAL, X-RAY, AND γ-RAY EMISSION

There are several regions in the outer magnetosphere of a rapidly spinning magnetized neutron star where canonically assumed currents will cause charge depletion and hence large potential drops along B to develop. 1) One such region may be expected where relativistic charge carriers of a single sign move out from the stellar surface along an open magnetic field line curving upward toward Ω (region (1) of Fig. 1). Because $|\hat{\Omega}\cdot\hat{B}|$ increases along the flow, the charge density of Eq (1) cannot be maintained if $j = \rho_0 c \hat{B}$ and $\nabla\cdot j = 0$ (Arons 1981). Since "adolescent" pulsars are expected to inject only positive ions into the near magnetosphere above the polar cap surface a charge depleted outer region with $\rho \neq \rho_0$ might develop. 2) A second such region would be expected where inward relativistically flowing charge moves on magnetic field lines which bend away from Ω, as long as only carriers of a single sign are initially involved (region (2) of Fig. 1). The resulting charge depletion ($|\rho| < |\rho_0|$) would follow from the same arguments which lead one to expect it for region (1). 3) This depletion could be especially strong if the inflowing current crossed the null surface $\Omega\cdot B = 0$ where the charge density needed to maintain $E\cdot B = 0$ reverses sign. Then the current of positive charges pulled to the polar cap from the near magnetosphere (to balance those being pushed out along other field lines) would be continued by negative charges moving toward the light cylinder in the outer magnetosphere beyond the null surface. This could result in a region of almost complete charge depletion (an "outer gap") around the null surface and a large potential drop there along B (region (3) of Fig. 1) (Holloway 1973, Cheng et al. 1976). But, at least in the shorter-period neutron stars with larger dipole moments, the magnitude of outer-magnetosphere potential drops will be limited by electron-positron discharges. These are of a different kind from those which limit the magnitude of potential drops just above the polar cap where the magnetic field is much larger. These outer discharges should generally give a double fan-shaped beam of γ-rays and often, as we shall see, a variety of other kind of coincident radiation. A double beam structure would be expected no matter which is the region of the outer discharge. In cases 1) and 2) above an observer who saw one beam from a discharge on one side of the star would generally also see a second from the other side of the star. Time delay and aberration would cause a wide separation unless the $e^{\pm}$ discharge was a distance from the star $r << c\ \Omega^{-1}$. But for case 3), the discharge from an "outer gap" about a null surface, both beams come from the same side of the star and would be separated by 190° only if $r << c\ \Omega^{-1}$ where aberration and time delay would be negligible. In addition to the double outer-gap beams the adolescent pulsar is presumed to generate an RF beam beginning just above the polar cap so that these beams may be observed, as is indeed seen in the Crab and Vela pulsars (cf. Fig. 2).

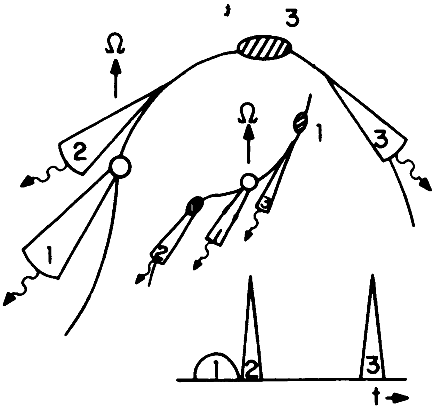

Fig. 2: Emitted beams and observed pulses from young adolescent pulsar. Beam 1 RF only

2.1 γ-Ray Emission

An "outer gap" will be limited by electron-positron production to that potential at which an e^- or e^+ produced in the "gap" radiates enough 10^9 eV photons there that one of those γ-rays makes another $e^\pm$ pair in the "gap". Because the local outer magnetosphere magnetic field is much less than 10^9 G, $e^\pm$ conversion of these γ-rays by the field is negligible even if the photons moved normal to $\underset{\sim}{B}$. Rather the GeV photons will collide with keV X-rays from the warm stellar surface or, in some cases, from a heated polar cap to produce a GeV $e^\pm$ pair (R 1980, CR 1980b). (The cross-section exceeds $(e^2/mc^2)^2 \sim 10^{-25}$ cm^2 as long as the center of mass energy is a few MeV.) The pairs will have a total initial energy $\sim$ 1 GeV and make a typical angle of order 10^{-1} rad with the local field in which they are created. Then each $e^\pm$ initially has $\gamma \sim 10^3$, $\gamma_\perp = \gamma 0 \sim 10^2$, and $\gamma_{11} = \gamma/\gamma_\perp \sim 10$ before acceleration in the gap. The gap potential needed to accelerate these $e^\pm$ to an energy sufficiently high that they can generate additional GeV γ-rays depends upon the local $\underset{\sim}{B}$. When it is weak enough that the time for the pair $p_\perp \sim \gamma_\perp$ mc to decay by synchrotron radiation,

$$\tau \sim \frac{m^3 c^5 \gamma_{11}}{e^4 B^2 \gamma_\perp} \sim \frac{10^{-4}}{B_6^2} \ \mathrm{s}\ , \tag{6}$$

is much greater than the time for the gap electric field to accelerate the e^+ and e^- to much higher γ_{11}, the $e^\pm$ in the gap and beyond act like heavy electrons of mass 10^2 m. To give them a $\gamma_{11} \sim 10^7$ so that they will radiate 10^9 eV curvature γ-rays requires 10^{15} V. The maximum potential drop available from outer gap charge depletion is $\Delta V \sim 10^{13}$ P^{-2} B_{12} (surface dipole) V so this could be achieved for fast pulsars like Vela (or even slower ones if $B_{12} >> 1$) which could then radiate over 10^{35} erg s^{-1} of high energy γ-rays at almost all angles within a full 90° of longitude. (Why the beaming in latitude is so much less is not clear.) Computed average spectra between 100 MeV and 10 GeV from such curvature radiation resembles that observed (Ayasli and Ögelman 1980).

A second pair of fan beams of extraordinarily high energy γ-rays, coincident in position with MeV-GeV beams, will be generated from inverse Compton scattering of thermal X-rays from the neutron star surface by the gap accelerated $e^\pm$. These Compton boosted γ-rays can have energies up to those of the primary $e^\pm$; the scattering cross-section $(\sigma \sim \sigma_T\ \ell n\ E^\pm/E^\pm)$ is smallest for the highest final energy γ-rays, which in addition have the shortest mean free path for conversion into $e^\pm$ pairs in the outer magnetosphere. Such absorption is followed immediately by synchrotron radiation from these pairs at somewhat lower energy but in almost the same direction as that of the initial photon as long as it moved at a small angle to the local $\underset{\sim}{B}$, so that the γ-ray energies will be reduced until the beam can finally penetrate through the outer magnetosphere. For Vela parameters and a surface thermal radiation $L_x \sim 10^{32}$ erg s^{-1} the total γ-ray power in this mode ($E_\gamma > 10^3$

GeV) is of order 10^{-2} of that in the GeV regime, and may be associated with the double beams of γ-rays of energies $\gtrsim 0.5 \times 10^{12}$ eV observed from the Crab and Vela pulsar (Bhat et al. 1981).

2.2 Vela Pulsar

The gap accelerated e^+ (e^-) directed inward (outward) toward the Vela pulsar stellar surface have an initial $\gamma_\perp \sim 10^2$ and $\gamma_{11} \sim 10^7$ in a field $B_6 \sim 1$. Since the current through the neutron surface corresponds to a particle flow $\dot{N} \sim \Omega^2 R^2 B\ (2\pi e)^{-1} \sim 10^{32}\ s^{-1}$ the initial power in this gap created particle flux is somewhat more than 10^{35} erg s^{-1}. Much of this is radiated away as curvature radiation of $10^{-1} - 1$ GeV but this still leaves about 10^{35} erg s^{-1} in particles flowing to the surface which would, if it reached the polar cap, heat it excessively. However, because $\underset{\sim}{B}$ increases greatly, as the surface is approached $\gamma_\perp$ increases as $B^{1/2}$ and γ_{11} decreases as $B^{-1/2}$ until the rate of synchrotron loss given in Eq (6) quenches $\gamma_\perp$. This occurs at about $B_6 \sim 10^3$, after which $\gamma_{11} \sim 3 \cdot 10^5$, and $\gamma_\perp \sim 1$. The power in particles impinging on the Vela polar cap and reradiated as X-rays is then only $\sim 2 \cdot 10^{31}$ erg s^{-1}. The lost synchrotron radiation is in the $1 - 10^8$ MeV interval.

2.3 Crab Pulsar

Faster pulsars than Vela inclined at the same angle, will have outer-gap magnetic fields which are greater by the ratio of P^{-3}. If $B_6 \gg 10^2$ synchrotron radiation reduces $p_\perp$ so quickly that the gap accelerated $e^\pm$ have the longitudinal inertia of a normal relativistic electron and the required curvature radiation energy could be achieved by a gap $\Delta V \sim 10^{13}$ V. For the Crab with outer magnetospheric $B_6 \sim 10 - 10^2$ G, synchrotron radiation alone from accelerated electrons with high γ_{11} may give enough GeV γ-rays within the gap with an intermediate ΔV. Thus, $\gamma_{11}\ \gamma_\perp^2\ eB\hbar/mc \sim 1$ GeV for $B_6 \sim 10$, $\gamma_\perp \sim 10^2$ and $\gamma_{11} \sim 10^5$ from $\Delta V \sim 10^{14}$ V. This is so much less than the maximum achievable ΔV from extensive outer gap charge depletion, that only a narrow accelerating region need be formed. Then the number of unaccelerated $e^\pm$ pairs formed by GeV γ-rays beyond the gap is huge compared to those formed within the gap because GeV γ-rays continue to be radiated by "primaries" beyond the accelerating region and because there is much more space for conversion to pairs there. For each e^+/e^- accelerated in opposite directions through the Crab pulsar's outer-magnetosphere gap potential drop, about 10^4 $e^\pm$ with $\gamma_\perp \sim 10^2$, $\gamma_{11} \sim 10$ will be created in the larger region beyond the gap where $\underset{\sim}{E} \cdot \underset{\sim}{B} \sim 0$. Then the following kinds of radiation are expected to be emitted from the region around an outer gap 10^{14} V potential drop in the outer magnetosphere of the Crab pulsar (all in double fan beams):

1) By the e^+/e^- gap accelerated primaries -

a) Curvature radiation of 10^2 MeV - 1 GeV γ-rays with $L_\gamma \sim 10^{36}$ erg s^{-1}.

b) Polar cap heating from the inflow of primaries, and of secondaries produced beyond the gap, resulting in $L_x \sim 10^{33} - 10^{34}$ erg s^{-1}.

c) Inverse Compton scattering by the primaries of surface and polar cap emitted X-rays to give an initial double beam of $\sim 10^3$ GeV γ-rays. [Unlike the similar beams from the Vela pulsar, that beam which must cross through the outer magnetosphere ($B \sim 10^7$ G) to be observed should not escape conversion to $e^\pm$ unless its energy is less than several x 10^2 GeV.]

2) By the $e^\pm$ secondaries produced beyond the accelerating region ($\gamma^\pm \sim 10^3$, $\gamma^\pm_\parallel \sim 10\ B_6 \sim 10$) -

a) Synchrotron radiation of energies 1 eV - 10 keV and intensity $\sim L_\gamma$. [A "toy-model" which assumes all pairs are created by monoenergetic X-rays and curvature γ-rays gives a synchrotron spectrum $dI/dE \sim E^{-n}$ with $n = 1/2$ compared to the observed $n \sim 0.9$. The estimated ratio L_{optical} (1 - 10 eV) to $L_{\text{X-ray}}$ (1 - 10 keV) is then about 1/30. The estimated optical pulse cusp is not much broader than that observed (Smith 1981).]

b) Inverse Compton boosted thermal surface and polar cap X-rays. Because the $\gamma^\pm_\perp$ of the secondaries drops during a) from 10^2 to 1 the final energy spread of these boosted X-rays is $\sim$ 10 keV - 10^2 MeV. (No quantitative estimates have been made of the spectrum; the stellar emission is not Planckean.)

3) According to the pulsar model discussed earlier the adolescent Crab would have a broad $\lesssim 10^{31}$ erg s^{-1} RF ($\sim$ 10 MHz) emission from just above the polar cap. Such a beam could illuminate the outer magnetosphere region from which all of the above emissions originate. (The near surface field is complicated in a young star and emission directions are not accurately predictable.) The dense relativistically streaming secondary $e^\pm$ plasmas, despite their constraint by a 10^7 G field, can give coherent inverse Compton scattering of the incident RF beam as long as that beam is not incident parallel to B in the stellar rest frame and the incident frequency satisfies $\nu_I < (\pi^{-1} n^\pm e^2 m^{-1} \gamma_\perp^{-1} \gamma_\parallel^{-3})^{1/2} \sim 10^8 - 10^9$ Hz. The Compton boosted RF has a characteristic frequency $\nu_F \sim \gamma_\parallel^2\ \nu_I \sim 10^2\ \nu_I$. This double beamed radiation would, in this model, be the harder spectrumed RF main pulse and interpulse of the Crab pulsar.

2.4 Other Pulsars

If all pulsars had the same magnetic moment and angle between it and $\underset{\sim}{\Omega}$, $\underset{\sim}{B}$ in outer gap regions would drop as P^{-3}. Then it would be difficult to achieve the needed 10^{15} V to maintain the $e^\pm$ outer discharge in slower pulsars unless $\underset{\sim}{\mu}$ were unusually large. But when $\underset{\sim}{\mu}$ makes an anomalously large angle with $\underset{\sim}{\Omega}$, so that the outer null surface gap is in a region with $B_6 \sim 10^2$, where strong synchrotron radiation reduces the effective mass of gap accelerated $e^\pm$ to m, only 10^{13} V may be needed to support an $e^\pm$ discharge and double γ-ray fan beams. (To achieve this the surface dipole field $B_{12} \gtrsim P^2$.) If the secondaries from such a discharge are illuminated by a canonical pulsar RF beam and coherently inverse Compton scatter it as we presume to be the case in the Crab pulsar, then in addition to the γ-ray beam there will be again two boosted RF beams. Because these are fan shaped they are probably more likely to be observed than the incident lower frequency beam. If the $e^{\pm}$ discharge is across the null surface (3) of Fig. 1, then the observed pulse separation would more closely approach 180° for longer P. Both would null together and have drifting subpulses in opposite directions if these reflected properties of the illuminating beam. These attributes are suggestive of those observed for pulses with widely spaced pulse interpulse structures (Manchester and Lyne 1977, Fowler et al. 1981).

I thank Andrew Cheng with whom most of the above has been discussed and developed and the John Simon Guggenheim Foundation.
† Research supported in part by the National Science Foundation.

REFERENCES

Arons, J.: 1981, this volume.
Ayasli, S. and Ögelman, H.: 1980, Astrophys. J. 237, p. 227.
Bhat, P., Gupta, S., Ramana Murthy, P., Sreekantan, B., Tonwar, S., and Viswanath, P.: 1981, this volume.
Cheng, A.: 1981, this volume.
Cheng, A. and Ruderman, M.: 1977, Astrophys. J. 214, p. 598 (CR).
Cheng, A. and Ruderman, M.: 1979, Astrophys. J. 229, p. 348
Cheng, A. and Ruderman, M.: 1980a, Astrophys. J. 235, p. 576.
Cheng, A. and Ruderman, M.: 1980b, preprint.
Cheng, A., Ruderman, M., and Sutherland, P.: 1976, Astrophys. J. 212, p. 808.
Cordes, J.: 1981, this volume.
Fowler, L., Wright, G.A.E., and Morris, D.: 1981, this volume.
Holloway, N.: 1973, Nature 246, p. 6.
Jones, P.: 1978, Mon. Not. R. astr. Soc. 184, p. 807.
Jones, P.: 1980, preprint.
Manchester, R.N. and Lyne, A.G.: 1977, Mon. Not. R. astr. Soc. 181, p. 761.
Michel, F.C.: 1974, Astrophys. J. 192, p. 713.
Michel, F.C.: 1975, Astrophys. J. 198, p. 683.
Pellat, R., Asséo, E., and Sol, H.: 1981, this volume.
Ruderman, M.: 1980, Ninth Texas Symp. on Relativistic Astrophys., New York Academy of Science 336, p. 409 (R).
Ruderman, M. and Sutherland, P.: 1975, Astrophys. J. 196, p. 51 (RS).
Smith, F.G.: 1981, this volume.
Sturrock, P.: 1971, Astrophys. J. 164, p. 529.

DISCUSSION

KIRK: Can you say how the two-stream instability could lead to charged bunches which are stable enough to radiate coherently in the radio band?

RUDERMAN: No. I have looked only at the time scale for instability growth and the related characteristic plasma frequencies, but not at the efficiency for conversion of the relative stream motion into coherent radiation.

KUNDT: Does the chemical composition of your pulsar winds change significantly with age? How large is the ionic fraction?

RUDERMAN: From the surface the relative fraction of protons and iron changes with age as does the strength of any accompanying electron-positron discharge. Because of further electron-positron production well above any accelerating polar cap gap the total number of such pairs will generally (but not always) exceed that of any other component.

ENDEAN: In terrestrial arc gaps, once they have broken down, they stay broken down. The voltage drops to a very low value, typically 10 V or so, and the electrode voltage drop distance becomes very short, certainly less than 10^{-5} cm. In the case of the pulsar polar cap, one might expect the increased surface work function to cause the voltage drop to increase to a kilovolt or so and the distance to decrease to about 10^{-7} cm. In the terrestrial case the electrode temperature does not matter. With cold electrodes field emission takes place. Why does the pulsar polar cap not behave in this way?

RUDERMAN: In the electron-positron discharges approximately 10^{12} V is needed to maintain the discharge once it has been initiated. If it drops below this there is no further production of pairs. To initiate the discharge, once it is extinguished, may indeed take significantly more potential drop than is needed to keep it going. If the electric field were reversed so that it could pull electrons, rather than ions, from the surface and if no pair production was relevant, the laboratory electron discharge analogy might be appropriate.