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Pulsar Death at an Advanced Age

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Not long ago Rankin (1990) presented strong evidence in favor of a low altitude ($r \approx R_*$) dipole geometry for the site of the core component of pulsar radio emission. Arons (1993) gave evidence that spun up millisecond pulsars must have a substantially dipolar large scale field at low altitute. Electron-positron pair creation at low altitude above the polar caps has long been hypothesized to be an essential ingredient of pulsar radio emission. If so, all observed pulsars must lie in the region of $P - \dot{P}$ space where polar cap acceleration has sufficient vigor to lead to the copious pair production. Yet, to date, all *internally consistent* theories of polar cap pair creation have required hypothesizing a large scale (eg, quadrupole) component of the magnetic field with strength comparable to that of the dipole, in contradiction with the evidence in favor of an apparently dipolar low altitude geometry. The internally consistent theories also violate other observational constraints. The discharge models of Ruderman and Sutherland (1975), Gurevich and Istomin (1985), and Jones (1977, 1978, 1979) all accelerate equal, counterstreaming flows of electrons and positrons, thus putting one half of the particle acceleration energy into high energy particle and photon bombardment of the polar caps. The heating causes pulsed thermal X-ray emission from hot spots in excess of what is seen (Ogelman 1993). While the Arons and Scharlemann (1979) model does not have this problem, since the space charge in the starvation zone above the polar cap is made up almost entirely of the outbound beam, in star centered dipole geometry it dramatically fails to account for pulsar emission over most of the $P - \dot{P}$ diagram and predicts radio polarization variations in contradiction to the observations (Narayan and Vivekanand 1982).

Here I describe a low altitude polar cap acceleration theory which successfully associates pulsar "death" with the cessation of pair creation in an *offset* dipolar low altitude magnetic field. The basic acceleration physics is that of a space charge limited relativistic particle beam accelerated along the field lines by the starvation electric field, as in the Arons and Scharlemann theory, with two effects from general relatvity added. The effect of inertial frame dragging, first pointed out by Muslimov and Tsygan (1992), causes the accelerating electric field to be about an order of magnitude larger than that calculated by Arons and Scharlemann for pulsars near the death line. Gravitational bending of gamma ray orbits is an order of magnitude greater than the bending of the dipole field lines incorporated in previously models to estimate the component of photon momentum perpendicular to B, *if the center of the dipole is offset from the stellar center by an amount δ greater than a polar cap diameter,* $\sim 0.1P^{-1/2}$ km $\ll R_* \sim 10$ km. The location of the death line depends on the magnitude of the offset, thus yielding a "death valley" (Chen and Ruderman 1993). If curvature emission is the only source of gamma rays, the edge of the valley (the outer

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envelope of pair creation activity in the $P - \dot{P}$ diagram) corresponds to a total polar cap voltage

$$\begin{aligned}\Phi_{cap,death} &= 0.8\frac{m_e c^2}{e}\frac{R_* c^2}{2GM_*}\left(\frac{\Omega_* R_*}{c}\right)^{3/8}\left(\frac{R_*}{\delta}\right)^{1/4}\left(\frac{R_*}{\lambda_C}\right)^{1/2}\left(\frac{R_{B*}}{R_*}\right)^{3/4} \\ &\approx 10^{13}(\sec i)^{3/4} R_{10}^{7/8}\frac{R_{10}^2}{M_{1.4}}P^{-3/8}\left(1-\frac{\delta}{R_*}\right)^{3/4} \text{ Volts.}\end{aligned}$$

where $\Phi_{cap} \equiv (\dot{E}_R/c)^{1/2} \propto (\dot{P}/P^3)^{1/2}$, $\dot{E}_R \equiv \mu^2\Omega_*^4/c^3$, μ is the magnetic moment, Ω_* is the stellar angular velocity measured by an observer at infinity, i is the angle between Ω_* and μ, R_{B*} is the smallest distance from the dipole center to the stellar surface, λ_C is the Compton wavelength, and the stellar moment of inertia has been assumed to be $I = 0.4M_*R_*^2$. The numerical value applies when δ is a large fraction of R_*, and encompasses all the known pulsars if the maximum offset is 75% of the stellar radius. Compton scattering of thermal photons from the cooling stellar surface and from the heated polar cap (Luo 1996) may reduce the amount of offset required to bring the model into satisfactory agreement with the observations of P and $\dot{P}$. This theory predicts millisecond pulsars die at relatively high voltage, $\Phi_{death,msp} \geq 10^{14.2}$ Volts. Thus, millisecond pulsars will *not* be found with values of $\dot{P}$ much smaller than those of the currently known objects.

Satisfactory agreement with the observations occurs at the price of introducing a special kind of magnetic anomaly (an offset dipole). This kind of anomaly, however, *is* consistent with the evidence adduced for low altitude dipolar structure in the magnetic fields of rotation powered pulsars.

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