A New Class of Radio Quiet Pulsars

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Abstract. The complete absence of radio pulsars with periods exceeding a few seconds has lead to the popular notion of the existence of a high \( P \) death line. In the standard picture, beyond this boundary, pulsars with low spin rates cannot accelerate particles above the stellar surface to high enough energies to initiated pair cascades through curvature radiation, and the pair creation needed for radio emission is strongly suppressed. In this paper we postulate the existence of another pulsar “death line,” corresponding to high magnetic fields \( B \) in the upper portion of the \( \dot{P} \)--\( P \) diagram, a domain where few radio pulsars are observed. The origin of this high \( B \) boundary, which occurs when \( B \) becomes comparable to or exceeds \( 10^{13} \) Gauss, is again due to the suppression of magnetic pair creation \( \gamma \rightarrow e^+e^- \), but in this instance, primarily because of ineffective competition with the exotic QED process of magnetic photon splitting. This paper describes the origin, shape and position of the new “death line,” above which pulsars are expected to be radio quiet, but perhaps still X-ray and \( \gamma \)-ray bright.

INTRODUCTION

Due to the broad range of period derivatives observed for isolated radio pulsars, the population spans over four decades in their estimated spin-down field strengths (e.g. Taylor, Manchester and Lyne 1993). However, none have inferred (dipolar) fields exceeding a few time \( 10^{13} \) Gauss, suggesting that there is an observational bias against observing high-field pulsars. This bias could be due to a complete absence of neutron stars with fields much above \( 10^{13} \) Gauss, or perhaps radio emission is somehow suppressed at such high field strengths, diminishing their observability. The former hypothesis has no intrinsic theoretical basis, and is contradicted by the suggestion (Duncan and Thompson 1992) that soft gamma repeaters have supercritical fields, above \( 10^{14} \) Gauss. Hence, it is of interest to examine the latter possibility, that high field pulsars do not produce radio emission; this is the focus of this paper.

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Magnetic one-photon pair production, $\gamma \rightarrow e^+e^-$, has traditionally been the only gamma-ray attenuation mechanism assumed to operate in polar cap models for radio (e.g., Sturrock, 1971) and gamma-ray pulsars (Daugherty & Harding 1982, 1996; Sturner & Dermer 1994), providing the means for both types of pulsars to radiate efficiently. Such an interaction can be prolific at pulsar field strengths, specifically when the photons move at a substantial angle $\theta_{kB}$ to the local magnetic field. Pair creation has a threshold of $2m_e c^2 / \sin \theta_{kB}$. The exotic higher-order QED process of the splitting of photons in two, $\gamma \rightarrow \gamma \gamma$, will also operate in the high field regions near pulsar polar caps and until very recently, has not been included in polar cap model calculations. Magnetic photon splitting has recently become of interest in neutron star models of soft gamma repeaters (Baring 1995), and Harding, Baring and Gonthier (1997) have determined that splitting will play a prominent role in the formation of spectra for PSR1509-58, the gamma-ray pulsar having the lowest high-energy spectral turnover, around $\sim 1$ MeV.

The key property of photon splitting that renders it relevant to neutron star environs is that it has no threshold, and can therefore attenuate photons below the threshold for pair production, $\gamma \rightarrow e^+e^-$. Hence, when it becomes comparable to $\gamma \rightarrow e^+e^-$, it will diminish the production of secondary electrons and positrons in pair cascades. Since pairs are probably essential to the generation of radio emission (e.g., Sturrock 1971), such a “quenching” of pair creation can potentially provide a pulsar “death-line” at high field strengths; this phenomenon is the subject of this paper. While about a dozen radio pulsars have spin-down magnetic fields above $10^{13}$ Gauss, little attention was paid to $\gamma \rightarrow \gamma \gamma$ in pulsar contexts prior to the launch of the Compton Gamma-Ray Observatory (CGRO) in 1991 because until then, the three known gamma-ray pulsars had estimated field strengths of less than a few times $10^{12}$ Gauss. The detection of PSR1509-58 by the OSSE and COMPTEL experiments on CGRO provided the impetus to focus on high-field neutron star systems.

**QUENCHING OF PAIR CREATION IN PULSARS**

In polar cap models, pair cascades in radio and gamma-ray pulsars are initiated by relativistic electrons either via curvature radiation (e.g., Daugherty and Harding 1982), or by their resonant (magnetic) Compton scattering (e.g., Sturner and Dermer 1994) with thermal X-rays that emanate from the stellar surface. The cascades are perpetuated and amplified by synchrotron radiation interspersed with generations of pair creation. The nature of these three processes is well understood. For relativistic electrons with Lorentz factor $\gamma$, photons produced by these mechanisms are collimated to angles $\sim 1/\gamma$ to the direction of the electron’s momentum. Furthermore, the produced radiation in each of these processes is highly polarized. The degree of polarization $P$ of synchrotron and curvature emission (they are identical: see, for example,
Jackson 1975) is \((p + 1)/(p + 7/3)\) for power-law electrons \(n_e(\gamma) \propto \gamma^{-p}\), and is in the 60\%-70\% range (e.g. see Bekefi 1966), favouring the production of photons in the \(\perp\) state. Here the label \(\parallel\) refers to the state with the photon’s electric field vector parallel to the plane containing the magnetic field and the photon’s momentum vector, while \(\perp\) denotes the photon’s electric field vector being normal to this plane. Likewise, it can be deduced from Herold’s (1979) expression for resonant Compton scattering in the Thomson limit that the upscattered photons are predominantly in the \(\perp\) state also, achieving \(P \sim 50\%\). Hence any pair creation in pulsars is primarily initiated by photons with polarization state \(\perp\), thereby simplifying the considerations here.

In this paper we will assess how effective photon splitting is relative to magnetic pair creation in attenuating photons that are produced by these radiation mechanisms. In doing this, we propagated photons outwards from some point on or above the stellar surface, computing their attenuation probabilities for both of these processes. Of specific interest is the escape energy, \(\varepsilon_{\text{esc}}\), the energy below which (for each mechanism) photons escape the neutron star magnetosphere without attenuation. We fully include the general relativistic effects of a Schwarzschild spacetime, and details of the geometry and propagation set-up are described at length in Harding, Baring and Gonthier (1997). In that work, which focused on the high-field test-case pulsar PSR 1509-58, it was clearly demonstrated that pair creation is suppressed when photon splitting dominates it at higher field strengths. Also, generally, larger polar cap sizes favour the suppression of cascades and hence radio emission.

We computed the magnetic fields \(B_d\) for given polar cap angles (colatitudes) \(\Theta\) for which the escape energies for splitting and pair creation were equal, so that for \(B \gtrsim B_d\) pair creation is strongly suppressed by splitting. Since the multiplicity of pairs in a pulsar cascade rapidly becomes large in just a few generations, quenching is extremely abrupt and effective at high fields. Therefore, we expect a rapid decline in pair creation and hence also radio luminosity when \(B\) rises above \(B_d\). Remembering that the polar cap size is coupled to the pulsar period \(P\) (in flat space time \(\Theta \approx (2\pi/P)^{1/2}(R_{\text{ns}}/c)^{1/2}\), and we included general relativistic corrections to this), the so-defined \((B, \Theta)\) relationship becomes a critical curve on the \(P - \dot{P}\) diagram. This curve delineates the phase spaces for radio-loud and radio-quiet pulsars, and examples are depicted in Figure 1, along with the latest population distribution from the Princeton pulsar catalogue. This boundary delineates a zone where pair creation is suppressed, like its long period counterpart. However, there is no pulsar evolution across the boundary (without field evolution): high field pulsars are born radio-quiet. Hence it is not a true death-line, just a border to the radio quiet region.

There are four examples of such boundaries in Figure 1 because the results differ according to the initial angles of photons with respect to \(B\), and their original location. For photons that start out almost along the field, as in a curvature radiation-initiated cascades (the solid curves), \(B_d \propto \Theta^{-1/3} \Rightarrow \dot{P} \propto \)
FIGURE 1. The $P$--$\dot{P}$ diagram for the latest Princeton Radio Pulsar catalogue (May 3, 1995: see also Taylor, Manchester and Lyne 1993) together with four possible high-field “death” lines (heavy solid and dashed curves), above which pulsars are radio-quiet. For the four cases depicted, the solid curves represent situations where photons that seed potential cascades (e.g. curvature radiation) are initially beamed very close to the field lines, while the dashed curves have such photons initially propagating at an angle of $0.57^\circ$ to the local field. For both these scenarios, the lower curves are for emission from the stellar surface, and the upper ones are for photons originating half a stellar radius above the surface. The light dotted diagonal lines define contours of constant $B$, as labelled, and three gamma-ray pulsars in the diagram are marked as indicated in the inset.
$P^{-5/6}$. When photons initially have appreciable angles to $B$, as can be the case in resonant Compton-initiated (IC) cascades, photon splitting competes more effectively with pair creation for smaller polar cap sizes and the “death-line” drops to lower field strengths. Clearly the position of the line, which marks surface fields, strongly depends on the radius of photon origin since the physics of this problem couples to the magnitude of $B$. Hence there is, at present, significant uncertainty in the location of the radio-quiet boundary, principally because the location of the acceleration of primary electrons is not fully understood. Note that ground state pair creation also becomes prevalent for high $B$ (Harding and Daugherty 1983), thereby aiding cascade cessation and lowering the radio-quiet boundary in the $P-\dot{P}$ diagram. Note also that there is marginal evidence for a drop in pulsar radio-luminosity when their fields exceed around $3 \times 10^{13}$ Gauss, contrary to the slow increase with $B$ seen for lower spin-down fields.

Clearly, when pair creation is suppressed and pulsars become radio quiet, they can still emit $\gamma$-rays prolifically, via the primary electrons and spectral reprocessing via splitting. Hence it is reasonable to conjecture that the radio quiet pulsars may actually be a class of objects formerly known as Gemingas. Motivations for searching for such $\gamma$-ray pulsars are therefore self-evident. Soft $\gamma$-ray observability is perhaps governed by $(B/P^2)^{1/2}$, favouring sources to the upper left of the $P-\dot{P}$ diagram, which should guide pulsar searches with OSSE and COMPTEL. On the other hand, hard $\gamma$-ray (i.e. EGRET, $> 100$ MeV) observability implies no spectral cutoffs (as in PSR1509-58), and favours small $\Theta$, in the upper right of the diagram (for high $B$). The very shapes of the “death-lines” in Figure 1 indicate that radio searches for high-field pulsars should focus on sub-second periods and high $\dot{P}$. In conclusion, in the polar cap model, the physics described here may well imply the existence of a radio-quiet pulsar population with high surface fields.

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