HIGHLY-MAGNETIZED PULSARS AND INTEGRAL

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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 period death line. We have recently postulated the existence of another radio quiescence boundary at high magnetic fields ($B \gtrsim 4 \times 10^{13}\text{ G}$) in the upper portion of the period-period derivative diagram, a domain where no radio pulsars are observed. The origin of this high $B$ boundary is also due to the suppression of magnetic pair creation, $\gamma \to e^\pm$, but mainly because of competition with the exotic QED process of magnetic photon splitting, $\gamma \to \gamma \gamma$, coupled with ground state pair creation. This mechanism could also explain the low spectral cutoff energy of the gamma-ray pulsar PSR1509-58, which lies near the high $B$ death-line. In this paper, we summarize the hypothesis of this new “death line,” and discuss some subtleties of pair suppression that relate to photon polarization and positronium formation. We identify several ways in which Integral will serve as a useful tool in probing high field pulsars, given that the radio quiescence boundary is transparent to the high energy bands.

KEYWORDS: pulsars: general — stars: neutron — magnetic fields — gamma rays: theory

1. HIGHLY-MAGNETIZED PULSARS

The study of pulsars with unusually high magnetic fields, namely $B \gtrsim 10^{15}\text{ G}$, has recently become of great interest in the astronomical community, due both to the rapid increase in observational data indicating such high fields, and also to the fascinating physics that might arise in their environs. Apart from a handful of conventional radio pulsars such as PSR 1509-58 with spin-down field estimates in the range $10^{13}\text{ G} \lesssim B \lesssim 3 \times 10^{13}\text{ G}$, there is the growing body of anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) perhaps with much larger fields. Such sources are currently being touted as candidate magnetars (e.g. Thompson & Duncan 1993), a class of neutron stars with fields in excess of $10^{14}\text{ G}$.

The AXPs are a group of six or seven pulsating X-ray sources with periods around 6-12 seconds, which are anomalous in comparison with average characteristics of known accreting X-ray pulsars. They are bright, steady X-ray sources having luminosities $L_X \sim 10^{35}\text{ erg s}^{-1}$, they show no sign of any companion, are steadily spinning down, and have ages $\tau \lesssim 10^5\text{ years}$. Those which have measured $\dot{P}$ (e.g. Mereghetti & Stella 1995; Gotthelf & Vasisht 1998) have derived dipole spin-down magnetic fields between $10^{14}$ and $10^{15}$ Gauss. The SGRs, so-named because of repeated transient $\gamma$-ray burst activity, are another type of high-energy source that has recently joined this group of possible magnetars. There are four known SGR sources (one newly discovered: Kouveliotou, et al. 1998b), two (SGRs 1806-20 and 0526-66) associated with young ($\tau < 10^5\text{ yr}$) supernova remnants. Recently, 7.47s and 5.16s pulsations have been discovered (Kouveliotou, et al. 1998a,c; Hurley et al.
1998) in the quiescent X-ray emission of SGRs 1806-20 and 1900+14, respectively, with SGR 1900+14 exhibiting a 5.15s period in a $\gamma$-ray burst (Cline et al. 1998), much like the original and canonical 5th March 1979 event from SGR 0526-66.

In the pulsar $P - \dot{P}$ diagram, both AXPs and SGRs live in a separate region above the detected radio pulsars: no radio pulsars have inferred fields above $\sim 3 \times 10^{13}$ Gauss, even though known selection effects do not a priori prevent their detection. Baring & Harding (1998a) have recently proposed an explanation for the absence of radio pulsars of such high magnetization. We identified a strong suppression of pair creation, $\gamma \to e^\pm$, in fields above $\sim 10^{13}$ Gauss, ultimately through the action of the exotic QED process of photon splitting $\gamma \to \gamma\gamma$. The splitting of one photon into two lower energy ones (e.g. Adler 1971), which is third-order in quantum electrodynamics (QED), can act as a competitor to pair creation $\gamma \to e^+e^-$ as an attenuation mechanism for gamma-rays; it has appreciable reaction rates (e.g. Adler 1971; Baring & Harding 1997) when $B > \sim 10^{13}$ Gauss.

The possible relevance of photon splitting for pulsars has recently received a dramatic boost from the new Comptel data (Kuiper et al. 1998) for PSR 1509-58. Harding, Baring & Gonthier (1997, hereafter HBG97) had discussed $\gamma \to \gamma\gamma$ in the context of this pulsar. They found that spectral attenuation by splitting at energies $E$ between a few MeV and just below 100 MeV could nicely accommodate the positive detections by Comptel (then up to around 3 MeV) and the severely constraining EGRET upper limits at $E > \sim 100$ MeV, provided that polar cap size $\Theta$ ranged between $\Theta \approx 2^\circ$ and $\approx 10^\circ$. Curved spacetime was incorporated in HBG97’s photon propagation calculations, with splitting (and not pair creation) effecting the predicted spectral cutoffs. The positive detection by Kuiper et al. (1998) of pulsed $\gamma$-rays in the 3–10 MeV band dramatically narrows the available model phase space. Spectral cutoffs consistent with the data now appear only possible for $\Theta \approx 2^\circ$, the standard polar cap size for PSR 1509-58, and then only provided photon splitting is acting and general relativity is incorporated in the model. In the absence of splitting, considerably larger $\Theta$ are required to fit the data with attenuation due to $\gamma \to e^\pm$. Such constraints strongly indicate the action of $\gamma \to \gamma\gamma$ in this source. Furthermore, the almost power-law Comptel data suggest that only the $\perp\to\parallel$ mode of splitting is operating (discussed in HBG97), a possible experimental verification of theoretical kinematic selection rules (Adler 1971).

2. RADIO QUIESCENCE

Presuming that a plentiful supply of pairs is a prerequisite for, and maybe also guarantees, coherent radio emission at observable levels, a premise of standard polar cap models for radio pulsars, an immediate consequence of the significant suppression of pair creation by splitting (and other effects mentioned just below) in pulsars is that detectable radio fluxes should be strongly inhibited. Baring & Harding (1998a) determined an approximate criterion for the boundary of radio quiescence in the $P - \dot{P}$ diagram based on a comparison of attenuation properties for $\gamma \to e^\pm$ and $\gamma \to \gamma\gamma$ in general relativistic neutron star magnetospheres. We
found that for $\dot{P}$ above $\dot{P} \approx 7.9 \times 10^{-13} (P/1 \text{sec})^{-11/15}$, photon splitting by the $\perp \rightarrow \parallel\parallel$ mode should dominate pair creation by $\perp$-polarized photons, corresponding to fields in the range $3 \times 10^{13} \text{G} \lesssim B \lesssim 8 \times 10^{13} \text{G}$. While $\parallel$-polarized photons can still produce pairs, they are in relative paucity due to the predominance of $\perp$ photons ($\gtrsim 75\%$) in the continuum emission processes of curvature and synchrotron (or cyclotron) radiation and resonant Compton upscattering (Baring and Harding 1998b). Clearly, the suppression of pair creation by splitting is partial, not total.

The robustness of this putative boundary for radio quiescence, which is computed specifically for photon origin near the stellar surface, can be fully assessed with a Monte Carlo cascade calculation. Yet, only moderate overall suppression of pairs per cascade generation is necessary to quench radio emission given the large pair multiplicities computed for standard pulsar polar cap cascades (e.g. Daugherty & Harding 1982). Baring and Harding (1998b) demonstrate that suppression of pair creation by splitting is quite effective when the continuum spectrum is as steep as $E^{-2}$, and/or the maximum photon energy is lower than around 1 GeV. They also find that for extended flat power-laws (to 10 GeV and above), splitting can actually enhance the number of pairs in one generation, principally because it generates numbers of $\parallel$ photons which then have a greater opportunity to create pairs than their $\perp$ counterparts, due to their lower pair threshold. Notwithstanding, the $\parallel$ photons produce pairs almost entirely in the ground (0,0) state, thereby preventing any further pair generations by inhibiting cyclotron emission.

Our determination of the quiescence boundary is effectively independent of whether free pair creation or positronium formation is considered (Baring & Harding 1998b); the thresholds for bound and free pair creation are extremely close (Usov & Melrose, 1995). The extent of dissociation of bound pairs has not been decisively determined at present (see Baring & Harding 1998b), so it is unclear whether positronium formation actually inhibits radio signals. Splitting is significantly aided in its suppressive action by the dominance of pair creation in the lowest accessible Landau state configuration when $B \gtrsim 6 \times 10^{12} \text{Gauss}$ (Harding & Daugherty 1983). In such fields, $\perp$-photons produce pairs no higher than the first Landau level so that subsequent cyclotron photons are mostly below pair threshold. Since $\parallel$-photons leave pairs in the ground state, they spawn no cyclotron/synchrotron emission. Hence pair cascading is strongly inhibited for $B \gtrsim 6 \times 10^{12} \text{G}$; as B is increased, $\gamma \rightarrow \gamma\gamma$ ultimately precipitates a dramatic reduction in the pair density. The picture can be modified by the possibility of resonant Compton scattering by pairs, effecting polarization mode switching of photons during traversal of the magnetosphere; this renders pair suppression by splitting more effective.

3. X-RAY/GAMMA-RAY PROPERTIES AND INTEGRAL

The radio quiescence boundary is transparent to Integral: pulsar X-ray and gamma-ray fluxes are not expected to be strongly correlated with the number of pairs. This is because cascading mechanisms merely redistribute the emission between the gamma-ray and X-ray bands without severe diminution of the overall
luminosity. Hence, high field pulsars should be accessible to Integral. One of
the potential gains from Integral will be its ability to probe the cyclotronic and
sub-cyclotronic structure in the spectra of high field pulsars. Integral's contin-
um and line sensitivities will permit exploration of spectral bumps and breaks at
the cyclotron fundamental. Furthermore, given a handful of sources, Integral can
search for trends with spin-down $B$. For example, as pair suppression ensues above
$\sim 6 \times 10^{12} \text{G}$, a decline on the number of pair generations and loss of the steeper
synchrotron component to spectra are expected, corresponding to flatter spectra
(case in point, PSR1509-58). At the same time, the cyclotron fundamental moves
up in energy. An observed coupling between such effects would strongly argue in
favor of the polar cap model for high energy pulsar emission. At the same time, the
issue of the apparent mismatch between Ginga and OSSE spectra for PSR1509-58
(e.g. see data in HBG97) should be resolved. In terms of the AXPs and SGRs, it is
unclear what role Integral will play. It is possible that Integral will be able to detect
or place significant upper limits to quiescent emission from SGR 1900+14, which
has periods of relatively flat spectra (Kouveliotou et al. 1998c). Integral should
certainly be capable of detecting any of the SGRs in outburst. However, extrapo-
lation of the steep RXTE spectra for the quiescent AXPs falls below the Integral
sensitivity. Hence Integral’s impact on studies of these sources is contingent upon
AXPs possessing another harder component to their emission.

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