Photon Attenuation and Pair Creation in Highly-Magnetized Pulsars

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Abstract

Developments over the last couple of years have supported the interpretation that anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) possess unusually high magnetic fields, and furthermore may represent a class or classes of neutron stars distinct from the population of conventional radio pulsars. We have recently suggested that such a dichotomization of the pulsar population may naturally arise due to the inherently different conditions in subcritical and supercritical magnetic fields. In this paper, we summarize, within the polar gap model, expectations for observable properties of highly magnetized pulsars, conventional or anomalous. This includes a discussion of the potential suppression of pair production and cascade generation in very strong fields by photon splitting and by threshold pair creation, which might explain radio quiescence in AXPs and SGRs. X-ray and hard gamma-ray spectral properties and trends are identified, with a view to establishing goals for future high energy experimental programs.

1 Introduction

The study of pulsars with unusually high magnetic fields, namely $B \gtrsim 10^{13}\,$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 dipole spin-down field estimates in the range $10^{13}\,\mathrm{G} \lesssim B_0 \lesssim 3 \times 10^{13}\,$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 $10^{14}\,$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 $L_X \sim 10^{35}\,\mathrm{erg\ s^{-1}}$, they show no sign of any companion, are steadily spinning down, and have ages $\tau \lesssim 10^5$ 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 γ-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), and two (SGRs 1806-20 and 0526-66) being associated with young ($\tau < 10^5$ 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 γ-ray burst (Hurley et al. 1999), 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 $\sim 10^{14}$ Gauss, even though known selection effects do not *a priori* prevent their detection. This motivated Baring & Harding (1998) to propose an explanation for the absence of radio pulsars of such high magnetization. We identified a potentially 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 $\gamma \to \gamma\gamma$. In this paper, we present results of a more detailed exploration of this issue, namely a determination of pair yields from simulations of pair cascades. Our computations indicate that photon splitting is generally only marginally effective at reducing the number of pairs when only one polarization mode ($\perp \to \|\|$) of splitting operates (according to kinematic selections rules derived by Adler 1971), due to significant pair production by photons of $\|$ polarization. In this case, ground state (threshold) pair creation significantly reduces the total number of pairs. If three polarization modes of splitting operate, then pair suppression is dramatic and the contention of Baring & Harding (1998) is borne out.

Throughout this paper, the standard convention for the labelling of the photon polarizations will be adopted, namely that $\|$ 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.

2 Pair Suppression and Radio Quiescence?

A premise of standard polar cap models for radio pulsars is that a plentiful supply of pairs is a prerequisite for coherent radio emission at observable levels. By extension, an immediate consequence of the significant suppression of pair creation by splitting in pulsars (and other effects mentioned just below) is that detectable radio fluxes should be strongly inhibited. Baring & Harding (1998) 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. They found that for $\dot{P}$ above $\dot{P} \approx 7.9 \times 10^{-13} \, (P/1\,\text{sec})^{-11/15}$, photon splitting by the $\perp \to \|\|$ mode should dominate pair creation by $\perp$-polarized photons, corresponding to fields in the range $3 \times 10^{13}\,\text{G} \lesssim B_0 \lesssim 8 \times 10^{13}\,\text{G}$, thereby defining the lower extent of a region of radio quiet pulsars. Underpinning this is the fact that while $\|$-polarized photons can still produce pairs, they are in relative paucity in multi-generational cascades 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 1999; hereafter BH99). 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 assessed with a Monte Carlo cascade calculation. We have developed (BH99) a simulation that extends the work of Harding, Baring and Gonthier (1997). It follows photons from a point above the stellar surface, along trajectories in curved spacetime, permitting them to split or create pairs, and then computing curvature and synchrotron/cyclotron radiation products of these pairs. Subsequent attenuation of these photons is determined, as are the next generation of pairs and their emission; a complete computation of photon-initiated pair cascades is thus obtained. The principal missing ingredient in this simulation is a consistent determination of the point of emission of the primary photon in conjunction with an acceleration region.

In Figure 1, we depict *pair yields*, the number of pairs produced per primary photon, for an input primary photon spectrum typical of that for curvature radiation from uncooled monoenergetic electrons. The photons assume a power-law of index $\alpha \sim 1.6$, cutoff of at various energies $\omega_{\text{max}} m_e c^2$, as indicated. The yields are functions of the surface field strength B_0, in units of the quantum critical field $B_{\text{cr}} = 4.413 \times 10^{13}$ Gauss. While the left panel of the Figure explores variations with the maximum photon energy, and differences obtained when photon splitting is present or is artificially suppressed, the right panel illustrates the effect of changing the polar cap size Θ (assumed to be in degrees here), or pulsar period $P \approx 0.69\Theta^{-2}$.

The first obvious feature is a drop in the pair yield at surface fields of $B_0 \sim 3 \times 10^{12}$ Gauss. When the local field is $B \gtrsim 6 \times 10^{12}$ Gauss, pair creation occurs predominantly in the lowest accessible Landau state configuration (Harding & Daugherty 1983). In such fields, $\perp$-photons produce pairs

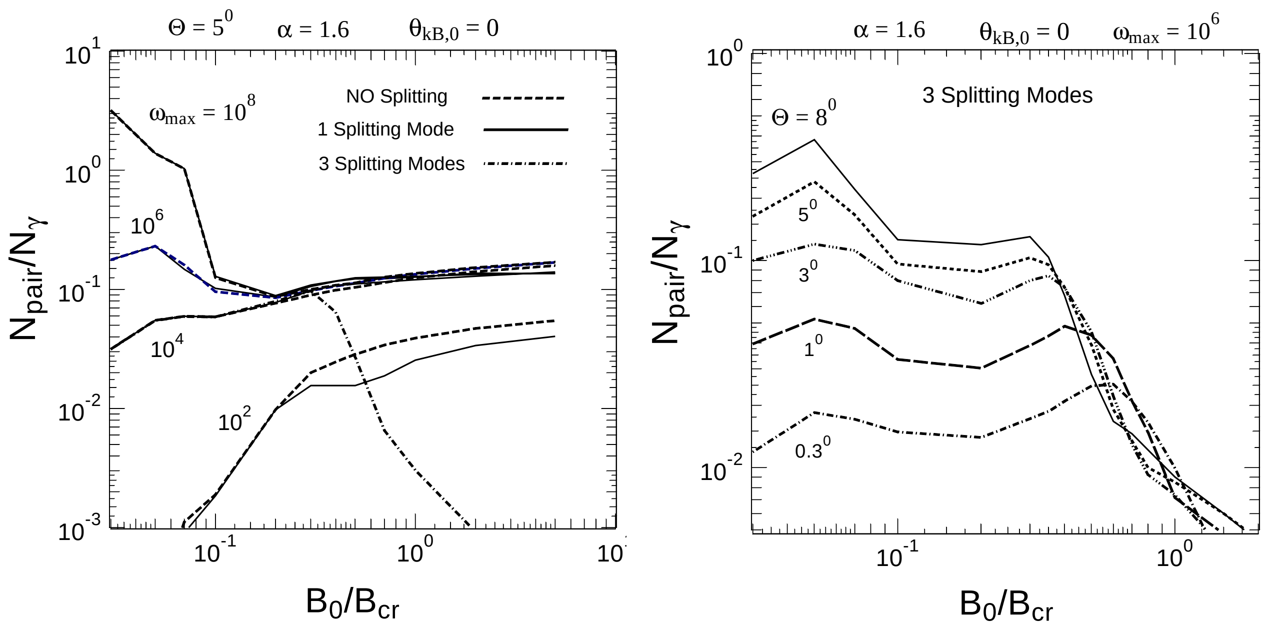

Figure 1: The cascade pair yield (number of pairs per injected photon) as a function of surface magnetic field strength, B_0, in units of the critical field, $B_{\rm cr}$. *(Left Panel)* Dependence of the pair yield on the maximum primary photon energy $\omega_{\rm max}$ (in units of m_ec^2) is displayed. Different line types refer to the cases where no splitting, only one mode, or three modes of splitting are allowed (see text). *(Right Panel)* Here the pair yields are exhibited for varying primary photon injection colatitudes, Θ, for the case where three photon splitting modes operate. Strong suppression of pair creation is afforded in these cases for high B_0.

no higher than the first Landau level so that subsequent cyclotron photons are mostly below pair threshold. Since $\|$-photons leave pairs in the ground (0,0) state, they spawn no cyclotron/synchrotron emission, preventing any further pair generations. Hence pair cascading is strongly inhibited for such local fields, and this appears as a decline in the pair yields for high $\omega_{\rm max}$ cases with large polar cap sizes. Next, the left panel indicates that, in the case of one splitting mode, the number of pairs produced per primary photon saturates at high fields to constant values that depend on the polar cap colatitude Θ and $\omega_{\rm max}$. This arises principally because the attenuation rates for both pair creation and photon splitting saturate in ultra-quantum fields. For really low B_0, the pair yield drops off, due to the associated decline in the pair creation rate. In the right hand panel, the correlation of pair yield with Θ just reflects the reduction in the pair creation rate with larger radii of field curvature. These last two trends putatively couple to the conventional death line for radio pulsars.

Inspection of the left hand panel of Figure 1 immediately reveals that there is miniscule reduction in the pair yield by the action of one polarization mode ($\perp\to\|\|$) of splitting in all but the lowest $\omega_{\rm max}$ case. The reason for this is twofold: (i) the onset of pair creation in the ground state at lower fields has already inhibited cascading to the point that there is little more that splitting can do, and (ii) the splitting $\perp\to\|\|$ actually creates more photons than it destroys, and all of these are available for pair creation at a somewhat lower threshold (than for $\perp$ photons). Hence, splitting actually both hinders and helps pair creation, the two tendencies effectively negating each other. This situation changes when all three splitting modes ($\perp\to\|\|$, $\perp\to\perp\perp$, $\|\to\perp\|$) allowed by CP invariance are permitted to operate. Then pair creation is rapidly quenched with increasing B_0, an effect whose onset B_0 declines with larger Θ, and matches well the predictions of Baring & Harding (1998). It is presently unclear how many modes of splitting operate in supercritical fields: assessment of this would be based on the extremely-involved calculation of higher-order quantum electrodynamical dispersive effects in the magnetized vacuum. Details of these results and discussion of these and other issues can be found in Baring and Harding (1999).

It is also salient to briefly address expectations for the X-ray and gamma-ray properties of highly-magnetized pulsars in their quiescent states. The radio quiescence boundary is transparent in such observational bands since 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. Since high field pulsars have cyclotron energies in the hard X-ray/soft gamma-ray range, soft and hard X-ray experiments will probe the cyclotronic and sub-cyclotronic structure in the spectra of high field pulsars. One expects these sources to exhibit spectral bumps and breaks near the cyclotron fundamental. Furthermore, given a handful of sources, experiments such as Integral can search for trends with spin-down field. For example, as pair suppression ensues above $\sim 3 \times 10^{12}$ 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. In addition, hard gamma-ray missions such as GLAST can explore the expected anti-correlation between the maximum observable photon energy (due to attenuation by pair production and photon splitting) and the surface field B_0, a prediction of the polar cap model that is difficult to replicate in outer gap scenarios. It is important to note that while these properties accommodate sources like PSR 1509-58, they are at odds with what little is known of the AXPs and SGRs, which display moderate to steep soft X-ray spectra in quiescence, as determined by RXTE and ASCA. It is possible that these steep spectra are an entirely different component from the curvature/inverse Compton/synchrotron cascade emission addressed in this paper.

References

Adler, S. L. 1971, Ann. Phys. 67, 599.
Baring, M. G. & Harding A. K. 1998, Astrophys. J. 507, L55.
Baring, M. G. & Harding A. K. 1999, in preparation.
Gotthelf, E. V. & Vasisht, G. 1998, New Astronomy 3, 293.
Harding A. K., Baring, M. G. & Gonthier, P. L. 1997, Astrophys. J. 476, 246. (HBG97)
Harding, A. K. & Daugherty, J. K. 1983, in Positron Electron Pairs in Astrophysics, eds. M. L. Burns, et al. (AIP Conf. Proc. 101: New York), p. 194.
Hurley, K. et al. 1998, IAU Circ. No. 7001.
Hurley, K. et al. 1999, Nature 397, 41.
Kouveliotou, C. et al. 1998a, Nature 393, 235.
Kouveliotou, C. et al. 1998b, IAU Circ. No. 6944.
Kouveliotou, C. et al. 1998c, IAU Circ. No. 7001.
Mereghetti, S. & Stella, L. 1995, Astrophys. J. 442, L17.
Thompson, C. & Duncan, R. C. 1993, Astrophys. J. 408, 194.