Mon. Not. R. Astron. Soc. **000**, 1–28 (2010) Printed 29 October 2018 (MN LaTeX style file v2.2)

Pair cascades in the magnetospheres of strongly-magnetized neutron stars

Zach Medin[1]* and Dong Lai[2]†
[1] *Department of Physics, McGill University, 3600 rue University, Montreal, QC H3A 2T8, Canada*
[2] *Department of Astronomy, Cornell University, Ithaca, NY 14853, USA*

ABSTRACT
We present numerical simulations of electron-positron pair cascades in the magnetospheres of magnetic neutron stars for a wide range of surface fields ($B_p = 10^{12}$–10^{15} G), rotation periods (0.1–10 s), and field geometries. This has been motivated by the discovery in recent years of a number of radio pulsars with inferred magnetic fields comparable to those of magnetars. Evolving the cascade generated by a primary electron or positron after it has been accelerated in the inner gap of the magnetosphere, we follow the spatial development of the cascade until the secondary photons and pairs leave the magnetosphere, and we obtain the pair multiplicity and the energy spectra of the cascade pairs and photons under various conditions. Going beyond previous works, which were restricted to weaker fields ($B \lesssim$ a few $\times 10^{12}$ G), we have incorporated in our simulations detailed treatments of physical processes that are potentially important (especially in the high field regime) but were either neglected or crudely treated before, including photon splitting with the correct selection rules for photon polarization modes, one-photon pair production into low Landau levels for the $e^{\pm}$, and resonant inverse Compton scattering from polar cap hot spots. We find that even for $B \gg B_Q = 4 \times 10^{13}$ G, photon splitting has a small effect on the multiplicity of the cascade since a majority of the photons in the cascade cannot split. One-photon decay into e^+e^- pairs at low-Landau levels, however, becomes the dominant pair production channel when $B \gtrsim 3 \times 10^{12}$ G; this tends to suppress synchrotron radiation so that the cascade can develop only at a larger distance from the stellar surface. Nevertheless, we find that the total number of pairs and their energy spectrum produced in the cascade depend mainly on the polar cap voltage $B_p P^{-2}$, and are weakly dependent on B_p (and P) alone. We discuss the implications of our results for the radio pulsar death line and for the hard X-ray emission from magnetized neutron stars.

Key words: radiation mechanisms: non-thermal – stars: magnetic fields – stars: neutron – pulsars: general.

1 INTRODUCTION

The pair cascade in the magnetosphere of a pulsar has long been considered an essential ingredient for the pulsar's nonthermal emission, from radio to gamma rays (e.g., Sturrock 1971; Ruderman & Sutherland 1975; Melrose 2004; Thompson 2004). More recently it has been suggested that the pair cascade is also necessary for nonthermal emission from magnetars (e.g., Beloborodov & Thompson 2007; Thompson 2008a,b; see Woods & Thompson 2006 for a review of magnetars). The basic pair cascade involves several steps: (i) acceleration of primary particles by an electric field parallel to the magnetic field; (ii) gamma ray emission by the accelerated particles moving along the magnetic field lines (either by curvature radiation or inverse Compton upscattering of surface photons); (iii) field-assisted photon decay into electron-positron pairs as the angle between the photon and the magnetic field line becomes sufficiently large, or pair production by two-photon annihilation in weak-field regimes; (iv) gamma ray emission by the newly-created particles as they lose their transverse energy through synchrotron emission; (v) further pair production and gamma ray emission via steps (iii) and (iv). The dense, relativistic (Lorentz factors $\gamma \gtrsim 100$) electron-positron plasma generated by this cascade is a required input in many models for the pulsar radio emission (e.g., Melrose 1995, 2004; Beskin 1999; Melikidze, Gil, & Pataraya 2000; Lyubarsky

* Email: zmedin@physics.mcgill.ca
† Email: dong@astro.cornell.edu