Part 6

Emission and Plasma Theory

Section C. Pair-Plasma Processes

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The Pair Cascade in Strong and Weak Field Pulsars

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Abstract. We have simulated the development of the pair cascade in a range of magnetic field strengths. We determined the efficiencies of lepton and secondary photon production, as well as the distribution functions of the pair plasma and of the escaping photons. We find the magnetic field has the most important effect on the cascade; primary beam energies and seed photon emissivities are of less importance.

1. The Pair Plasma in Pulsars

Most students of pulsar physics think that a pair plasma is important in the magnetosphere. In addition to being important in the global structure and dynamics of the magnetosphere, the pair plasma is a key ingredient in most radio emission models. However, the emission mechanism is still far from being understood. Quite a few different models of plasma emission and propagation have been proposed over time, and several were presented at this meeting. Important parts of these models depend critically on microscopic details of the putative pair plasma, but these details have not yet been determined. We find it wearisome to undertake long calculations (such as plasma wave modes or instability growth rates) when the foundation of such calculations, *i.e.* the plasma distribution function, is not known.

The formation and properties of the pair plasma are also crucial issues in polar cap models. The plasma, if it forms, increases the conductivity of the magnetosphere, enabling premature shorting out of the accelerating electric field, which in turn limits the overall energetics of the polar cap region. But, since the energetics of this region drive the pair cascade in the first place, a full model of the process must include both accelerating fields and the pair cascade self-consistently. We find this a daunting prospect. We therefore choose to isolate one piece of it: the development and saturation of the cascade.

We have done this numerically. With a new code, we extend the work of Daugherty & Harding (1982) by exploring parameter space more fully, particularly studying the pair plasma. Arendt & Eilek (2000) report the full details. In this short paper we present highlights of the calculation and some general thoughts on the connection between pairs and pulsar physics.

2. Development of the Cascade

We begin by recalling the basic picture of cascade development. Rotation-induced electric fields pull charged particles from the polar cap and accelerate them to relativistic energies. These form the "primary beam". In long-period pulsars, these particles probably have energies $\gamma_b \sim 10^4 - 10^5$ if the acceleration is limited by inverse Compton scattering, and $\gamma_b \sim 10^6 - 10^7$ if they are accelerated through the full rotation-induced potential drop. A primary beam particle will radiate *via* inverse Compton scattering (on thermal photons from the warm star), or *via* curvature radiation. In either case the radiation is in the γ-ray band. In the strong magnetic fields of pulsars, these photons can be susceptible to one-photon pair creation. We call these "seed" photons.

A seed photon makes an electron-positron pair if two conditions are satisfied. The reaction must be allowed energetically: $\epsilon_\perp = h\nu \sin\theta / m_e c^2 > 2$ (the photon's momentum and energy transverse to $\mathbf{B}$ are relevant here). In addition, the optical depth of the magnetosphere to pair creation must be at least unity. This condition can be expressed as $\epsilon_\perp B \gtrsim 0.1 B_{cr} \simeq 4 \times 10^{12}$G. In high fields, the energetic limit determines whether pair creation occurs or not; in low fields the opacity condition is more important. If either lepton is created in a Landau level above the ground state, it will decay by emission of synchrotron photons. These photons can create pairs themselves, leading to a pair avalanche, or pair cascade. The cascade ends when all photons can escape the magnetosphere and when all leptons are in their lowest Landau levels.

We have written a numerical code to follow both the photons and leptons forward in space and time during such a cascade. Our calculation has two parts. We first pick monoenergetic seed photons and determine the cascade they produce. We then use these results as "kernels" and integrate over the photon spectrum produced by a primary beam particle undergoing either curvature radiation or inverse Compton losses. We choose primary beam energies as given above, and magnetic fields from 10^{11}G to 10^{13}G, representative of the range thought to exist in single pulsars.

3. Results of the Cascade

In following the cascade, we find that the magnetic field is by far the most important parameter. In strong fields, $B = 10^{13}$G, we find almost no secondary photons; the leptons are created in the Landau ground state, and the cascade terminates in one generation. For moderate fields, $B = 10^{12}$G, the cascade continues through several generations. The weakest fields we used, $B = 10^{11}$G, had either no cascade (due to transparency) or quite weak ones. These weak-field cascades were also copious photon producers, which made the computations harder.

The final distribution function of the leptons (after the cascade has terminated and all synchrotron emission has ceased) can be described simply. In a frame moving with the plasma, the leptons' distribution is well described by a cool Maxwellian, at a temperature $k_B T \lesssim m_e c^2$. When transformed to the star's frame, at a mean Lorentz factor $\gamma_p \sim 100 - 200$ (10^{12}G) or, $\gamma_p \sim 300 - 2000$ (10^{13}G), the lepton distribution appears warmer, that is broadly peaked with an

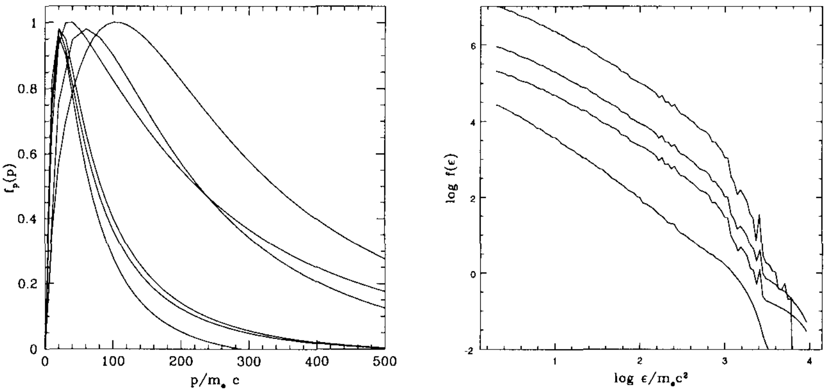

Figure 1. Left, lepton distribution functions for several runs with $B = 10^{12}$G. Both curvature radiation and inverse Compton seeds are represented, for a range of primary beam energies. Right, photon spectra similarly; the high-energy tails show artifacts of small numbers and finite energy bins. Arbitrary vertical scaling has been applied to make the figures clear.

extended high-energy tail. The shape of the lepton distribution is only slightly sensitive to B.

The final photon spectrum is also calculated after the cascade has ended; it thus represents "escaping" photons which could be observed directly. The photon spectrum shows a stronger dependence on B than the lepton spectrum does. This is due to the presence, or absence, of secondary synchrotron photons which can escape the region. Higher B fields produce flatter photon spectra; with few synchrotron secondaries, only the primary photons which happened not to pair produce will be seen. Lower B fields will produce steeper spectra, due to the abundant secondary synchrotron photons created.

We also determined the multiplicity, $\mathcal{M}$, and energy conversion for these cascades. $\mathcal{M}$, defined as the number of pairs produced per primary beam particle, ranges from a few to a few hundred, substantially smaller than typical estimates used in the literature, which assume $\mathcal{M} \sim \gamma_b/\gamma_p$. In most cascades, less than half of the primary beam energy goes to the pair plasma; the rest comes out in photons or is not radiated at all. The exception here is an inverse Compton-seeded cascade in high B fields, which has nearly 100% energy-conversion efficiency.

4. Consequences for Pulsar Physics

Radio emission and propagation models depend on the distribution functions of the underlying plasma. We were pleased to find that the distribution function has a simple form (a cool Maxwelian in the comoving frame), and that form is quite insensitive to some parameters which vary star to star, such as the surface magnetic field strength and the primary beam energy. Other factors are more important, however: the energy efficiency and multiplicity of the pair cascade do depend on magnetic field and seed photon energy.

One might argue that the magnetic field is well constrained by a star's period and spindown rate (unless there are strong, higher multipoles close to the surface). The seed photon energy, however, depends on the primary beam energy, and on the radiation mechanism. These choices depend on basic questions still unsolved: just how particles are accelerated, by what effective electric field, and what role does the pair creation play in this process? What is the relative importance of inverse Compton radiation, and curvature radiation, in the process?

Another, related area, is still unclear: are there pairless pulsars? This depends on the opacity of the magnetosphere to pair creation, which depends (again) on the seed photon energy and the primary beam energy. Old, slow, single pulsars may or may not host pair cascades; whether they do or not depends on these uncertain details (two different views can be found in Weatherall & Eilek 1997, Arons 1999). Similarly, millisecond pulsars may or may not have pair plasmas. If they have the low fields which their periods and spindown rates suggest, then much higher seed photon energies are needed to initiate a cascade. This is possible, as they may have stronger accelerating potentials; but again, the physics here is not well understood. There seem still to be many interesting problems for us to study.

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