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Physics of the Radio Emission Region

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Abstract. The radio emission process in pulsars is still a mystery. It will help us all if the "theorist's freedom" in allowed models can be reduced. In order to do this, high quality data must be considered carefully in the light of existing or new theories, and the theories must be extended to address the data.

1. Introduction

If we are to understand the radio emission mechanism, we must understand the physical state of the radio-loud plasma in the polar cap. It is this plasma that is the site of instabilities which are thought to produce coherent radio emission. Platonic speculation aside, our best approach to this problem is to let the data lead us. In this paper I present some methods by which I hope to combine theory with data to determine physical conditions in the radio-loud region.

2. Signal Propagation and Polarization

The polar cap plasma is believed to be a magnetized, nearly charge-neutral pair plasma, moving out at relativistic speeds along the open field lines. It will have characteristic polarization and dispersion effects which can be useful as diagnostics.

2.1. Circular Polarization

Consider a cold pair plasma at rest (that is in the comoving frame of the polar cap plasma), with relative streaming (at v_o) of the electrons and positrons. I have derived dispersion relations and polarization conditions for this system, when $v_o \ll c$. I find that the O mode (the one which which couples to the plasma) is circularly polarized when it propagates close to **B** (Eilek 1996a). Transforming to the observer's frame, the angles θ showing significant circular polarization (CP) for high frequencies are

$$\omega \gg 2\sqrt{\gamma}\omega_p \qquad \Rightarrow \qquad \text{CP if} \qquad \theta^2 \ll \frac{\omega}{\Omega_o}\frac{\Delta\gamma}{8\gamma^4} \tag{1}$$

and for low frequencies,

$$\omega \ll 2\sqrt{\gamma}\omega_p \qquad \Rightarrow \qquad \text{CP if} \qquad \theta^2 \ll \frac{\omega_p^2}{\omega\Omega_o}\frac{\Delta\gamma}{\gamma^3} \tag{2}$$

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Here, $\Omega_o = eB/mc$ is the lepton cyclotron frequency; $\omega_p^2 = 4\pi ne^2/m$ is the (squared) lepton plasma frequency. (Equation 1 recovers the result of Kazbegi, Machiabeli & Melikadze 1991; the low frequency result seems to be new.)

This result seems most interesting in the low-frequency limit, which probably describes observed radio emission. The allowed angle increases going to lower frequencies (going below the comoving plasma frequency; note that propagation close to **B** is allowed in a magnetized pair plasma). This calls to mind the prevalence of CP in steep-spectrum coral emission (Rankin 1983), suggesting that it is a byproduct of the local emission process which tends to lower frequencies. In addition, one might speculate that the linear polarization of conal emission arises as a propagation effect, from propagation in the more curved field lines towards the edge of the polar cap.

2.2. Propagation in the Polar Cap

Consider a cold pair plasma moving at a bulk γ (as seen in the observer's frame). Solving the dispersion relation in the $B \to \infty$ limit, without relative streaming (as in Arons & Barnard 1986), I find that interesting effects occur for propagation close to the field (Eilek 1996b). The angular limit here is $\theta^2 \ll 4\omega_p/\gamma^{3/2}\omega$. For these angles, the dispersion relation has a flatter frequency dependence than that of the ISM. This will give a high-frequency signature of propagation in the polar cap. In particular, the arrival time of a pulse obeys

$$t_p(\omega) \simeq \pm\frac{1}{\nu}\int \frac{\nu_p}{\gamma^{3/2}}\frac{dr}{c} \tag{3}$$

where the integral is taken over the polar cap; and $\nu_p = \omega_p/2\pi$. For comparison, the ISM result is $t_p(\nu) \propto 1/\nu^2$. (The two signs correspond to the two modes which can propagate in this regime). In addition, scattering broadening leads to a pulse width,

$$t_D \propto \frac{\nu_p^2}{\gamma^3\nu^2}\left(\frac{\delta n}{n}\right)^2 \tag{4}$$

where $\delta n/n$ describes the density fluctuations due to turbulence. For comparison here, the ISM result is the much steeper $t_D \propto 1/\nu^4$.

This result says that signal propagation can be used as a direct measure of conditions in the polar cap. Measurement of the flatter t_p and t_D signatures at high frequencies will confirm the detection (*e.g.* Hankins & Moffett 1996 for the Crab pulsar). Once detected, the amplitude of the effects contains information on the polar cap density, streaming speed and turbulence levels. In Eilek (1996b), I show that these effects should be detectable with current techniques for a polar cap with a strong pair cascade.

3. The Pair Cascade in the Polar Cap

The above analysis follows the standard assumption, that a strong pair cascade raises the polar cap density well above the Goldreich-Julian density, and provides the site of plasma instabilities which lead to the radio emission. When standard pair cascade theory is compared to observations, however, it becomes clear that we are very far from the final answer.

3.1. Tracking Pair Formation

My colleagues and I (Eilek, Arendt & Gisler 1996) are developing a numerical code which follows the onset and development of the pair cascade. We are extending the Daughtery & Harding (1982) work in order to study the resultant pair distribution function, and how it depends on the polar cap conditions. At present we seed the cascade with photons distributed uniformly over the polar cap; we follow pair formation and synchrotron radiation in detail, until the cascade stops and the polar cap becomes fully transparent. This provides further diagnostics for the polar cap.

One diagnostic is simple opacity. One-photon pair production in a B field requires that the polar cap be opaque. If ϵ is the photon energy in units of $m_e c^2$, opacity requires the product $\epsilon B \sin\theta$ to be greater than a threshold value; our simulations with seed photons emitted within $\sim 2°$ of the local vertical, in a dipole field, find $\epsilon B >\sim 2 \times 10^{13}$G is required for opacity. The seed photons are often thought to come from curvature radiation. The mean photon energy from this process in a dipole field, if γ_b is the primary beam energy, is $\epsilon <\sim 0.6\gamma_b^3/P^{1/2}$. Thus, we should expect a strong pair cascade for high γ_b (that is, strong potential drops and short periods) and for high B fields.

Another diagnostic is the development of the cascade for an opaque star. The dependence of the opacity on θ results in the cascade being stronger around the edges of the polar cap (given our uniform distribution of seed photons). We find the pair density is highest along the LOFL, and decreases inwards toward the magnetic axis; in lower-B or lower-ϵ runs pair formation ceases altogether in the center of the polar cap. The preferential emission of seed photons along the outer, more curved field lines will enhance this edge effect; the central regions should not contain many pairs. In addition, the cascade from a single injection of photons develops and ends very quickly; our slowest (lowest ϵB cases) take only few nsec to develop, and our fastest go much faster. It is possible the slowest cascades might contribute to short-time microstructure (Hankins, these proceedings).

3.2. Observational Tests

With quantitative results in hand, this standard picture can be compared to the data. I am working on two approaches.

One method uses high S/N profiles to determine the spatial distribution of emissivity, $j(\rho, r)$; in altitude (r) and in distance from the magnetic axis (ρ). I use a profile simulation code, which predicts intensity as well as polarization direction, for forward-beamed radiation in a low-altitude dipolar polar cap. Applying this about a dozen well-known pulsars, both coral and conal, I can determine the emission altitude, and then deproject to turn observed pulse phase into ρ (Eilek, Hankins & Rankin 1996). This quantifies what we are all familiar with. That is, conal emission rises going away from the magnetic axis towards the edge of the polar cap; while coral emission is strongest on axis, and drops sharply moving outwards. Comparing this to the pair code results, is it obvious that standard pair theory produces conal pulsars. Coral emission, however, does *not* fit into the standard picture. If it comes from pairs, the seed photons for the cascade must be preferentially emitted along the magnetic axis.

Another method connects the pair opacity to profile shapes. If the seed photons for the cascade come from curvature radiation, the (ϵ, B) plane that is critical for opacity can be converted to the $(\dot{P}, P)$ plane of observed pulsars. (The connection for ϵ is through the potential drop that the polar cap can support). Weatherall & Eilek (1996) point out that the opacity condition, calculated honestly, falls squarely in the midst of observed pulsars in the $(\dot{P}, P)$ plane; this defines a more physical "death line" than the simple $\epsilon > 2$ energy condition quoted by some authors. Weatherall & Eilek also show that this death line neatly separates conal and coral pulsars (as taken from Rankin 1990) in this plane.

Comparing these two approaches leads us to an interesting contradiction. According to standard pair formation theory, coral pulsars should be pair opaque; but the pair formation should avoid the magnetic axis, which is the radio-loud region in a coral star. Conal pulsars, on the other hand, have the right distribution of radio emissivity to be a consequence of pair formation; but their potential drops are not strong enough to support the necessary seed photons. They should not contain any pair cascade.

4. Conclusions

Both of these directions look promising. Detection of the high-frequency propagation signal will give us a direct measure of conditions in the polar cap; circular polarization detects relative streaming in the plasma. Tracking the pair cascade has pointed out serious flaws in current models; we need to revisit the plasma origins in both cone and core emission.

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