Plasma around compact objects

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Plasma processes in pulsar magnetospheres

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Abstract. It is pointed out that the standard model for pulsar electrodynamics is based on a false premise, related to neglecting the displacement current, and the associated need for current screening. Wave dispersion in the standard model is reviewed, and its relation to the interpretation of pulsar radio emission and its polarization is discussed. Inclusion of the displacement current results in large-amplitude oscillations; some of the implications of these oscillations on the interpretation of the radio emission are discussed.

Keywords. pulsars: general, plasmas, magnetic fields, polarization

1. Introduction

Pulsar radio emission is poorly understood. In one sense, our failure to identify the emission mechanism unambiguously seems surprising. There is an enormous body of observational evidence on radio pulsars, and one would expect this to severely constrain the emission mechanism. Moreover, the number of possible mechanisms is relatively small (I comment on four) and one would expect to identify signatures that could distinguish between them. However, the difficulties in identifying the mechanism uniquely are formidable. On the theoretical side, our understanding of pulsar electrodynamics contains serious deficiencies, and it is unrealistic to suppose that we can predict the emission mechanism from first principles. On the observational side, although there are many rules that describe the huge variety of features in pulsar radio emission, there are exceptions to every rule. Furthermore, it is strongly believed that the emission is generated by relativistic particles, and for highly relativistic particles many features of the emission depend on the Lorentz factor, γ, and are insensitive to differences between different emission mechanisms. One might hope to identify the mechanism from the observed polarization, but evidence on orthogonally polarized modes (OPMs) strongly suggests that the observed polarization is determined as a propagation effect, rather than being intrinsic to the emission mechanism. When all the difficulties are taken into account, the concern is whether it is even possible in principle to identify the pulsar emission mechanism unambiguously.

There is a widely accepted standard model for pulsar magnetospheres, but this is based on a false premise. Criticism of the standard model is far from new (Michel 2004), and the assumption that I criticize specifically is that electric fields can be screened by charges: this is possible only if one neglects the displacement current and such neglect is justified only for an aligned rotator, which cannot produce any pulses. Available alternative models have other difficulties, and none has received wide acceptance. One can hope that an acceptable theory for pulsar electrodynamics will ultimately emerge, and that it will contain many of the features in the standard model. One new feature in such an acceptable model should be large-amplitude electric oscillations (LAEWs). As argued by Sturrock (1971) and confirmed by numerical calculations (Levinson *et al.* 2005, Beloborodov & Thompson 2007), when the displacement current is included, the magnetosphere is unstable to the development of LAEWs. Models for wave dispersion and pulsar radio emission are affected substantially by LAEWs. Here I make a distinction between a "standard" model without LAEWs and an "oscillating" model with LAEWs.

I discuss pulsar electrodynamics in §2, wave dispersion in a standard model in §3, pulsar radio emission mechanisms in §4, and some implications of an oscillating model in §5.

2. Pulsar electrodynamics revisited

Pulsar electrodynamics involves attempting to reconcile two incompatible models: a rotating magnetized star in vacuo, and a corotating magnetosphere. The standard model is based on an aligned rotator in which the electric field is not a function of time, but such a model does not pulse. For an oblique rotator, the electric field is intrinsically time-dependent, and the displacement current cannot be neglected.

Rotating dipole model: A rotating point dipole, $\mathbf{m}$, has time derivatives $\dot{\mathbf{m}} = \boldsymbol{\omega} \times \mathbf{m}$, $\ddot{\mathbf{m}} = \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{m})$, where $\boldsymbol{\omega}$ is the angular velocity. Using labels dip = dipolar, ind = inductive, rad = radiative, with $r_L = c/\omega$ the light cylinder radius, the magnetic field has terms with three different dependences of the radial distance, r. These are $\mathbf{B}_{\rm dip} \propto 1/r^3$, $\mathbf{B}_{\rm ind} \propto 1/r_L r^2$, $\mathbf{B}_{\rm rad} \propto 1/r_L^2 r$. The associated electric field has two such terms: $\mathbf{E}_{\rm ind} \propto 1/r_L r^2$, $\mathbf{E}_{\rm rad} \propto 1/r_L^2 r$. The leading term in the displacement current is $\varepsilon_0 \partial \mathbf{E}_{\rm ind}/\partial t \propto 1/r_L^2 r^2$.

Magnetic dipole radiation: The radiation field $\mathbf{E}_{\rm rad}, \mathbf{B}_{\rm rad}$ dominates at $r \gg r_L$, and leads to electromagnetic radiation at frequency ω, which carries away energy and angular momentum. The radiative energy loss is used to infer the slowing down, and hence to determine the dipolar component of the magnetic field at the stellar surface, $B_{\rm dip} \propto (P\dot{P})^{1/2}$ with $\omega = 2\pi/P$, and the age of the pulsar, $P/2\dot{P}$.

Quadrupolar electric field: Assuming that the interior of the star is a perfect conductor, there is a corotation electric field, $\mathbf{E}_{\rm cor} = -(\boldsymbol{\omega} \times \mathbf{x}) \times \mathbf{B}$, inside the star, $r < R_*$. The boundary conditions at the surface of the star imply a "quadrupolar" field $\mathbf{E}_{\rm quad} \propto R_*^2/r_L r^4$ at $r > R_*$. $\mathbf{E}_{\rm quad}$ has a component along $\mathbf{B}_{\rm dip}$, which rips charges off the surface of the star, populating the surrounding region with charges of one sign, and invalidating the vacuum model.

The rotating-dipole-in-vacuo model is unacceptable: the radiation cannot escape to infinity, and even if it did, the model predicts that the magnetic and rotation axes become aligned on the spin down time, which is inconsistent with observations.

Corotating model: In a corotating model, it is assumed that the corotation electric field, $\mathbf{E}_{\rm cor}$, is the only electric field in the magnetosphere. The divergence of $\mathbf{E}_{\rm cor}$ implies the Goldreich-Julian charge density, $\rho_{\rm GJ} = -2\varepsilon_0 \boldsymbol{\omega} \cdot \mathbf{B}_{\rm dip} \propto 1/r_L r^3 +$ other terms. In the standard model, $\mathbf{E}_{\rm quad}$ rips charges off the star, setting up $\rho_{\rm GJ}$ immediately above the star, but an additional source of charge is needed to provide $\rho_{\rm GJ}$ elsewhere in the magnetosphere. Further acceleration of the "primary" charges ripped off the star trigger a pair cascade, localized in a pair formation front (PFF). These "secondary" pairs provide the additional charges needed to screen $\mathbf{E}_{\rm quad}$ above the PFF.

Current screening: In an aligned rotator, the only electric field outside the star is $\mathbf{E}_{\rm quad}$, and because it is a potential field it can be screened by charges. In general, for $\mathbf{E}_{\rm cor}$ to be the only electric field, one must also screen $\mathbf{E}_{\rm ind}$, and this requires a screening current, $\mathbf{J}_{\rm screen} = \varepsilon_0 \partial[\mathbf{E}_{\rm ind} - \mathbf{E}_{\rm cor}]/\partial t \propto 1/r_L^2 r^2$. The usual assumption made in the literature is that the magnetosphere is stationary in a corotating frame, which involves neglecting

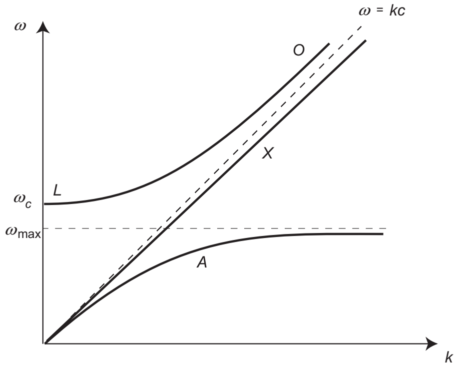

Figure 1. Dispersion curves for a pulsar plasma well below the cyclotron resonance: the cutoff is in the L-O mode, and the resonances is in the Alfvén (A) mode. Not shown is a small region near $\omega_c\gamma$ for nearly parallel propagation, where the O-mode dispersion curve crosses the light line (shown dashed), cf. (Melrose *et al.* 1999).

the displacement current, so that this screening current is zero by hypothesis. However, the displacement current is the proverbial "elephant in the room" and its neglect is not justified, and when it is included LAEWs develop.

The existence of the screening current has not been pointed out previously, and its implications have yet to be thought through in detail. The screening current is similar to the current, $\rho_{\rm GJ}\boldsymbol{\omega}\times\mathbf{x}$, due to the rotating charge density, in that it has the same radial dependence, $\propto 1/r_L^2 r^2$, but unlike this current it is not in the azimuthal direction, and it has a component across the magnetic field lines. For example, one implication is that if the density of pairs is not uniform across the field the required relative flow of electrons and positrons to produce the screening should set up a charge separation.

3. Wave dispersion in pulsar plasma

The standard, or polar-cap, model (Goldreich & Julian 1969, Ruderman & Sutherland 1975) is based on an aligned rotator, with $\mathbf{E}_{\rm quad}$ confined to a "gap" below a PFF. Above the PFF, the only electric field is $\mathbf{E}_{\rm cor}$. The secondary pairs, created in the PFF, radiate away their perpendicular energy, forming a 1D pair plasma with $p_\perp = 0$. The primary particles, with $\gamma \gtrsim 10^6$, that trigger the cascade form a beam propagating through this pair plasma.

Wave dispersion in a pulsar plasma is relatively simple low in the polar cap, where radio frequencies are much smaller than the cyclotron frequency, $\omega \ll \Omega_e/\gamma$. The natural modes are then linearly polarized (Barnard & Arons 1986). The X mode has vacuum-like properties. The O mode has a cutoff at $\omega \approx \omega_p/\gamma^{1/2}$. A beam instability is possible in the O mode at $\omega \approx \omega_p\gamma^{1/2}$, where its refractive index is greater than unity for small angles of propagation (Melrose *et al.* 1999). The Alfvén mode exist at $\omega \leqslant \omega_{\rm max} \approx \omega_p/\gamma^{1/2}$. These properties are illustrated in Fig. 1.

The radio evidence for orthogonally polarized modes (OPMs) is strongly indicative that the polarization is affected by the wave properties near the cyclotron resonance. Indirect evidence on the heights of the source of the radio emission (Gupta & Gangadhara 2003) favors heights well below where the wave frequency is equal to the cyclotron frequency. A plausible interpretation is that the observed polarization is the result of propagation effects modifying the polarization as the radiation passes through the cyclotron resonance. To discuss the interpretation of OPMs one needs a model for the wave dispersion near

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the cyclotron resonance. The simplest model is to assume that the plasma is cold in its rest frame and that electrons and positrons stream with the same Lorentz factor. This model may be treated by solving for the wave dispersion in the rest frame, and Lorentz transforming to the pulsar frame (Melrose & Luo 2004). Near the cyclotron resonance itself, the spread in Lorentz factors of the electrons smears out the resonance. The natural modes are elliptically polarized near the cyclotron resonance.

The interpretation of the OPMs requires mode coupling in two stages (Wang, Lai & Han 2010). Assuming that the emission is in a single mode, one stage is to produce a mixture of two modes, due to twisting of the magnetic field. The other is to produce the observed polarization, involving elliptically polarized modes, which requires a polarization limiting region near the cyclotron resonance.

4. Radio emission mechanisms

Pulsar radio emission has an extremely high brightness temperature, T_B, and an acceptable emission mechanism must be "coherent" in the sense that it can account for very high T_B. There are three coherence mechanisms: emission by bunches (particles localized in $\mathbf{x}$ and $\mathbf{p}$); a reactive instability (particles localized in $\mathbf{p}$), and a maser growth, which is equivalent to negative absorption. Emission by bunches requires an effective bunching mechanism, and none has been identified; moreover, the back reaction to the coherent emission tends to disperse a bunch (Melrose 1981), so that any bunching instability rapidly evolves into a reactive instability. A reactive instability evolves very rapidly, and the back reaction to it causes a spread in $\mathbf{p}$, so that a reactive instability evolves into a maser instability. For coherent emission from an astrophysical source to be observable requires emission from a relatively large volume for a relatively long time, and without a compelling argument to the contrary, a maser mechanism is implied. I outline four maser emission mechanisms that have been proposed for pulsars.

Plasma-like emission: A relative streaming motion in the ouflowing relativistic particles can lead to a beam instability that generates O mode waves in the small range where the condition $n_O^2 > 1$ is satisfied (Melrose *et al.* 1999). Unlike the Langmuir waves in a nonrelativistic plasma, the dispersion curve for the O mode allows these waves to escape. One problem with this mechanism is in identifying an effective relative streaming motion, to give the energy inversion, $df(\gamma)/d\gamma > 0$, required to drive the instability.

Curvature emission: In the simplest treatment, curvature emission is synchrotron-like in that maser emission is not possible. Maser emission is possible when the curvature drift motion is included or when the magnetic field is twisted. The mechanism also requires $df(\gamma)/d\gamma > 0$ (Luo & Melrose 1995).

Linear acceleration emission: LAE is due to acceleration by $E_\parallel$. It is particularly relevant in an oscillating model when $E_\parallel$ is present as a LAEW (Luo & Melrose 2008). Maser emission is possible for LAE (Melrose & Luo 2009); as for plasma-like emission and maser curvature emission, maser LAE requires $df(\gamma)/d\gamma > 0$. Maser emission is not favorable for LAEWs that cause the electrons and positrons to oscillate with highly relativistic amplitudes.

Anomalous cyclotron emission: Anomalous cyclotron resonance causes electrons (or positrons) in their ground state to jump to their first excited state while emitting a photon, and this requires that the refractive index be greater than unity. The resonance conditions is $\omega - s\Omega - k_\parallel v_\parallel = 0$, with $s = -1$ (Lyutikov 1999). For the frequency to be in the radio range requires that the magnetic field be relatively weak, so that the source region would be far from the star.

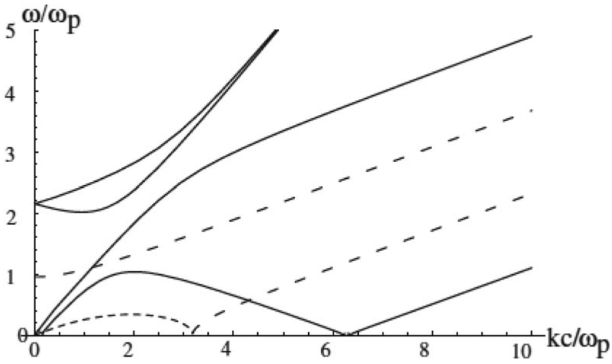

Figure 2. Dispersion curves ω vs k in normalized units for parallel propagation in a cold counter-streaming plasma with $\beta = 0.3$, $\Omega_e = 2\omega_p$. Dotted lines show imaginary parts, dashed lines show longitudinal real parts and solid lines show transverse real parts (Verdon & Melrose 2008).

An argument against maser emissions, and hence against any of these specific maser mechanisms, is that the most extreme examples of pulsar radiation, giant pulses, have T_B seemingly too large to be explained by any of them. A suggested alternative is that the emission is associated with an intrinsically nonlinear instability, similar to the collapse of Langmuir turbulence (Hankins & Eilek 2007).

5. Implications of an oscillating model

For an oblique rotator, inclusion of the displacement current leads to an instability, causing a LAEW to develop. As the (electric) amplitude of the LAEW increases, the maximum Lorentz factor of the oscillating particles increases proportional to it. Once the amplitude exceeds the threshold for effective pair creation, mass loading by pairs limits the amplitude of the LAEW.

In my opinion, the development of oscillations should be an essential feature of any acceptable model for an oblique rotator, and hence for any radio pulsar. It is implausible that the oscillations are coherent over large distances across field lines. Along any individual field lines the LAEW has a dominant effect on the distribution of electrons and positrons, causing them to counter-stream with an oscillating counter-streaming velocity corresponding to the Lorentz factor $\sim 10^6$ needed to generate pairs.

The effect of counter-streaming on wave dispersion in the simplest case of a cold plasma for parallel propagation is illustrated in Fig. 2. Dispersion curves for counter-streaming cold electrons and positrons are illustrated in Fig. 2. The parameters chosen in Fig. 2 are for convenience in illustrating all branches in a single figure. For small but non-zero angle of propagation, the dispersion curves do not cross, as they do in Fig. 2.

Counter-streaming leads to instability, which can result in plasma-like emission. The dispersion curves include an intrinsically growing mode at low frequencies, and in the neighborhood of the crossing points for parallel propagation (Verdon & Melrose 2008). The growth rate of the low-frequency mode decreases with increasing γ, and the most effective growth is at the phase of the LAEW where the counter-streaming is mildly relativistic. The periodic variation causes the wave frequency to change periodically, and a given wave can experience a burst of growth at the same phase over many periods of the LAEW. This is similar to plasma-like emission in the standard model, with the growth of radiation at a specific frequency occurring at a specific phase of the LAEW rather

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than at a specific height in the magnetosphere. An obvious advantage of the oscillating model is that the required streaming motions are intrinsic to the model.

Mode coupling associated with the cyclotron resonance occurs at a phase of the LAEW where γ is such that Ω_e/γ equals the frequency of the radiation. A theory for mode coupling in a time-dependent magnetized plasmas is needed to discuss such mode coupling in detail.

6. Conclusions

Electrostatic screening of the vacuum field through the Goldreich-Julian charge density is adequate only in an aligned model. In a realistic case a current density is also needed to screen the inductive electric field of the obliquely rotating magnetic dipole, and to set up the postulated corotation electric field. The neglect of the displacement current in models for pulsar electrodynamics obscures an important aspect of the physics: the magnetosphere of an oblique rotator is violently unstable to the development of LAEWs. The properties of wave dispersion in the standard model based on an aligned rotator are reviewed, as are four maser emission mechanisms that have been considered as the pulsar radio emission mechanism.

In an oscillating model, which assumes LAEWs are present, various new possibilities arise for the interpretation of pulsar radio emission. In particular, plasma-like emission and mode coupling to produce OPMs occurs in a similar way to the standard model. The important change is that these effects occur in time, at specific phases of the LAEW, rather than at specific locations as in the standard model. Effective growth of a counter-streaming instability occurs at the phase where the counter-streaming speed is comparable with the intrinsic spread in velocities, when the growth rate is maximum. The mode coupling required to produce observed OPMs is most effective at the phase where the cyclotron frequency, Ω_e/γ is minimum. These effects are currently being investigated.

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