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Whence the pulses?

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Abstract. Radio emission mechanisms for pulsars are reviewed with emphasis on five possible sites for the emission: the pair production front (PPF), two regions in the relativistically outflowing plasma (denoted ROP1 and ROP2) between the PPF and the light cylinder (LC), and two sited near the LC. Several maser emission mechanism are viable for ROP1, where radius-to-frequency mapping applies. Suggested Schott radiation from outside the LC is discussed critically.

1. Introduction

The title of my paper is taken from that of a panel discussion session "From whence the pulses?" at IAU Symposium 95 in 1980 (Sieber & Wielebinski 1981, p. 135), which ended up as a debate on polar cap versus light cylinder models as the source of pulsar radio emission. Pulsar radio emission was also discussed in detail at IAU Colloquium 128 in 1990 (Hankins, Rankin & Gil 1992), but no consensus emerged concerning the answer to this question. Here I review progress since 1980 in our understanding of where and how the radio emission from pulsars is generated.

In one sense the progress has been substantial. On the observational side, the discoveries of millisecond pulsars and of γ-ray emission from several radio pulsars have provided important new constraints on models. Moreover, the proposed distinction between core and conal emissions (Rankin 1983), although controversial, has led to a recognition that there appear to be qualitatively different types of pulsar radio emission. These are distinguished by their the radiation patterns, frequency spectra and polarization characteristics. Specifically, a highly polarized, core component is more common in younger pulsars, and conal emission occurs in older pulsars. Different emission mechanisms may be needed to explain these different types of pulsar radio emission. Moreover, scintillations have been shown to offer a possibility of resolving the source region observationally. On the theoretical side, the plasma physics on which theories for pulsar radio emission are based has reached a much higher level of sophistication, as reviewed at this meeting by Asseo. From a different viewpoint, there has been some notable progress in our understanding of maser emission processes in nearby (heliospheric) space plasmas, as discussed below. Our improving understanding of these other forms of coherent emission provides an indication of what is and is not reasonable to expect of any theory for pulsar radio emission.

In another sense, progress in our understanding of pulsar radio emission has been modest. We still do not have unambiguous identifications of either the location of the source of the radio emission within the pulsar magnetosphere or of the emission mechanism that produces it.

A standard model for a pulsar is assumed here: the magnetosphere of a rotating (angular speed Ω) magnetized neutron star is populated by pairs generated at a pair production front (PPF) in the polar cap, which is defined by the locus of the field lines that extend beyond the light cylinder (LC) at radius $r_{\rm LC} = c/\Omega$. In the literature one can identify at least five possible locations for the source of the radio emission: 1) the PPF, 2) in the relativistically outflowing plasma (ROP1) just above the PPF where the polar-cap field lines define a narrow diverging cone, 3) in the relativistically outflowing plasma (ROP2) at a substantial fraction of $r_{\rm LC}$ where the polar-cap field lines define a broad cone, 4) just inside the LC due to relativistic azimuthal motions, and 5) just outside the LC due to superluminal motion of the charge and current pattern. The older ideas concerning location 4) are not discussed further here (cf. Ferguson 1981).

A model for pulsar emission should account for the frequency spectrum, the angular dependence defined by the pulse window and the polarization. In ROP1 models, the emission from a given height is assumed to be relatively narrow in frequency, about a characteristic frequency that decreases with height, so that the frequency spectrum is attributed to a radius-to-frequency mapping (RFM). In all other models the frequency spectrum must be intrinsic to the emission mechanism. In both ROP1 and ROP2 models the angular distribution is determined by relativistic beaming along the local magnetic field lines, so that the geometry of the magnetic field determines the radiation pattern.

2. Location of source of the radio emission

The strongest evidence for ROP1 models is from RFM. However, RFM is not valid for all pulsar emission, and at least for those cases where it is not valid, one or more of the alternative emission sites may well apply.

2.1. ROP1 and ROP2 models

A ROP1 model provides a natural explanation for a commonly observed increase in size of the pulse window with decreasing frequency, which is well modeled by the broadening of the emission cone defined by dipolar-like field lines diverging with height. A ROP1 model implies not only RFM, but also a time of arrival (TOA) delay, with lower frequencies arriving before higher frequencies. Observational tests of RFM and TOA led to somewhat different conclusions by Thorsett (1992) and Cordes (1992) at IAU Colloquium 128. Thorsett concluded that the data on RFM and TOA raise as many questions as they attempt to solve, and Cordes concluded that RFM is viable for some but not necessarily all objects. For eight pulsars to which RFM plausibly applies, Cordes (1992) placed limits on the (ROP1) source heights of $\sim 100\,{\rm km}$ to $\sim 0.01\, r_{\rm LC}$.

Until recently, the arguments for a ROP2 model have been primarily theoretical, e.g., the cyclotron model of Machabeli & Usov (1979). At this meeting Manchester proposed a specific interpretation of highly-polarized, widely-spaced pulses in some young pulsars in terms of emission on a very broad cone or fan beam. This appears to be consistent with a ROP2 model, with the emission from polar cap field lines as they spread out to fill a large solid angle at a distance r that is a sizable fraction of $r_{\rm LC}$ (e.g., Yadigaroglu & Romani 1995).

Strong support for either ROP1 or ROP2 is provided by the characteristic sweep of linear polarization across the pulse window. This is consistent with any emission mechanism that produces linear polarization along or perpendicular to the magnetic field in the source region.

Interstellar scintillations (ISS) have produced some tantalizing results that suggest the possibility of resolving the emission region observationally (Cordes, Weisberg & Boriakoff 1983; Wolszczan & Cordes 1987), but the results are not definitive enough to identify the radio emission mechanism unambiguously.

2.2. High frequency emission

A small number (~ 7) of radio pulsars are observed to emit γ rays, implying a high power output in energetic pairs (e.g., Daugherty & Harding 1996). Any correlation between the γ rays and the radio emission might provide information on the source regions for both. However, the relation between the γ-ray and radio sources is unclear (e.g., Ulmer 1994, cf. Yadigaroglu & Romani 1995 however). In some of these pulsars the source of the γ-rays is more compatible with a ROP1 model, and in others more with a ROP2 model. Even if one were to postulate a relation between the source regions of the radio emission and γ rays, no unambiguous inferences could be drawn from the γ-ray data concerning the source of the radio emission.

2.3. Millisecond pulsars

The properties of the radio emission from millisecond pulsars is remarkably similar to that from many ordinary pulsars (e.g., Backer 1995). This suggests a criterion for acceptable pulsar radio emission mechanisms: the radio emission mechanism should not depend strongly on parameters, such as Ω, $r_{\rm LC}$ and B, that are very different for the two classes of pulsars.

3. Broadband emission models

It has long been known that some radio emission, notably microstructure, is relatively broadband, whereas RFM presupposes narrowband emission. Moreover, Rankin's (1983) proposed core emission and Manchester's proposed interpretation of some highly polarized emission suggest that more than one radio emission mechanism may be operating. Thus a broadband emission mechanism may be operating, presumably in addition to the narrowband mechanism associated with ROP1, and broadband emission is traditionally associated with LC and PPF models.

3.1. Schott radiation

An interesting suggestion for LC emission is that radiation can result from a corotating charge and current distribution that extends to beyond the light cylinder (da Costa & Kahn 1985; Ardavan 1992, 1994; Endean 1995). The idea is that *rigid rotation* may extend beyond the light cylinder where the charge and current pattern moves superluminally, with individual particles remaining subluminal. Such rigid rotation implies that the dependence on azimuthal angle, ϕ, and time, t, is only through the combination $\phi - \Omega t$. The resulting radiation is called Schott radiation (da Costa & Kahn 1985; Ardavan 1992). This mechanism is qualitatively different from earlier models for LC emission (e.g., Ferguson 1981) that rely on individual radiating particles reaching very high Lorentz factors as they approach the LC from inside.

The treatment of Schott radiation involves using the Lienard-Wiechert potentials (LWP), written down by Schott (1912) for a charge moving around a circle at faster than c. The LWP are singular whenever the projection of the velocity along the line of sight passes through c. (At these points the retarded time passes from real to imaginary.) Ardavan (1994) and Endean (1995) argued that the singular surface in the radiation pattern sweeping across the observer produces a pulse of radiation that provides a possible model for the pulses observed from pulsars.

A criticism of this mechanism, as a pulsar emission mechanism, concerns the requirement for emission at pulsar radio frequencies. The rigid-body rotation assumption implies that the emission consists of harmonics, $\omega = n\Omega$, of the rotation frequency. The power radiated at the nth harmonic is proportional to $|\mathbf{J}_n|^2$, where $\mathbf{J}_n$ is the nth order term in the expansion of the current density $\mathbf{J}(\phi - \Omega t)$ in a Fourier series. As noted by Ardavan (1992), for ordinary pulsars one requires harmonic numbers $n \sim 10^8$. Thus the observed emission must be attributed to very small structures, of size $\sim 2\pi r_{\rm LC}/n$, in the current pattern. A criticism of Schott radiation as a pulsar emission mechanism is that there is no obvious way in which such small-scale structures could form as a rigidly rotating pattern that moves superluminally. That is, there appears to be no physical justification for the assumption that the required very small-scale structures should depend only on the combination $\phi - \Omega t$. Any perturbation or instability in a superluminally rotating structure will lead to structures that depend separately on the coordinates and time.

LC models do not appear favorable when one requires that they apply to both ordinary and millisecond pulsars. There is an enormous range of $r_{\rm LC}$, and yet the emission pattern should look similar over this range. In the context of Schott radiation, with $n \sim 10^{11}$ for millisecond pulsars, for the radiation pattern to remain roughly the same for the two classes of pulsars requires a similar (fractal type) pattern, at least over the range $n \sim 10^8$–10^{11}.

3.2. PPF emission

In standard models, the secondary pair plasma that populates the magnetosphere is formed at a pair production front (PPF), where energetic γ rays produced through curvature emission by primary particles decay into pairs (e.g., Arons 1979). There is a net charge in the PPF, such that the parallel electric field that accelerates the primary particles below the PPF is screened above the PPF. Any motion or other temporal change of the PPF should produce radiation, e.g., due to it acting like an oscillating current sheet and radiating (Lerche 1970). Emission from the PPF appears to be consistent with Rankin's (1983) suggestion that core emission is due to a broadband source below the range of heights where conal emission is generated. A plausibility argument for emission from the PPF is that one would expect the screening at the PPF of the parallel electric field, that accelerates particles below the PPF, to be subject to violent variations (e.g., sparking). Some radiation must result. However, it does not necessarily follow that this radiation is observationally important.

A suggestion made by Ables & McConnell at this meeting may be regarded as related to a PPF model. The idea is that due to the divergence of the field lines in the polar cap, there is a diverging current density, **J**, as charges flow away from the pulsar. The angular pattern of the emission is a diffraction pattern. This provides a plausible explanation for the angular pattern seen in emission from a specific pulsars, adding further weight to the suggestion that there may be more than one intrinsically different radio emission mechanisms operating in pulsars.

4. Polar cap radio emission mechanisms

My views on emission mechanisms in polar cap models have been reviewed elsewhere (Melrose 1992a,b, 1995), and the following is a brief summary. A preliminary point is that, based on what we know about coherent emission processes in other astrophysical and space plasmas (section 5), a maser emission process is intrinsically more plausible than other forms of coherent emission. Three types of maser emission processes need to be considered.

The most widely favored and most plausible emission mechanism may be described as *relativistic plasma emission.* A maser process, typically a streaming instability driven by a distribution with $df(\gamma)/d\gamma > 0$, produces turbulence, and as a result of nonlinear processes or mode conversion (e.g., due to inhomogeneities) this turbulence is partially converted into escaping radiation. There are several detailed models for such emission, reviewed here by Asseo. The frequency of the resulting emission is determined by the local plasma frequency, $\omega_p \propto (\Omega B)^{1/2}$, and the Lorentz factor, γ, of the particles that drive the instability.

A second possible mechanism is a maser version of *linear acceleration emission* (e.g., Melrose 1978, Rowe 1992a,b). This requires an oscillating (in space or time) electric field parallel to the magnetic field, and then the emission is at $\omega \sim \omega_0\gamma^2$, where ω_0 is the oscillation frequency and γ corresponds to the range with $df(\gamma)/d\gamma > 0$.

A third possible mechanism is *maser curvature emission.* The proof that this is not possible (Blandford 1975; Melrose 1978) breaks down either when the curvature drift is taken into account (Luo & Melrose 1992), or when the field lines have torsion (Luo & Melrose 1995), in the sense that they have two orthogonal radii of curvature. Either mechanism can lead to maser curvature emission in principle. The characteristic frequency of the maser emission due to torsion is $\sim \gamma^3 c/r_{\rm curv}$, where $r_{\rm curv}$ is the radius of curvature of the field lines, and γ corresponds to the range with $df(\gamma)/d\gamma > 0$.

The requirement that the emission mechanism depend on parameters that are similar for ordinary and millisecond pulsars rules out only the variant of curvature maser that relies on the curvature drift. The parameters $(\Omega B)^{1/2}$, $r_{\rm curv}$ and γ on which the other mechanisms depend are similar for the two classes of pulsars, and the other mechanisms could all apply to both classes of pulsars. Of these mechanism, only variants of relativistic plasma emission have been modeled in sufficient detail for comparison with observations. Although some such variant is probably the most plausible mechanism, curvature maser emission due to field line torsion and linear acceleration emission remain apparently viable alternatives. Detailed models based on them need to be developed further.

5. Nature of maser emission mechanisms

There are now three well recognized coherent emission processes in astrophysical and space plasmas (e.g., Melrose 1991): plasma emission, electron cyclotron maser emission (ECME) and pulsar radio emission. Of these, pulsar radio emission is the least understood, and it is relevant to ask what useful insights ongoing developments in our understanding of the other two might shed on pulsar radio emission.

Plasma emission involves Langmuir turbulence, generated by a streaming or other instability, being partially converted into escaping radiation at $\sim \omega_p$ and $\sim 2\omega_p$. The theory of plasma emission has been tested by spacecraft passing through the source regions in the solar wind, planetary bow shocks, and the upper ionosphere. The general features of the theory have been confirmed. However, in all cases the Langmuir waves are distributed in a highly inhomogeneous manner – in isolated clumps. Despite this complication, relatively simple theories, such as one-dimensional quasilinear theory (Grognard 1984) and stochastic growth theory (Robinson, Cairns & Gurnett 1993; Robinson 1995), seem to work well in describing the large-scale average properties of the coupled particle-wave system.

The favored version of ECME is due to a loss-cone feature in the distribution of precipitating energetic electrons. In situ spacecraft data on the source region for the Earth's auroral kilometric radiation and data on Jupiter's decametric radiation from the flybys of Jupiter have provided complementary tests that confirm the general predictions of the theory. However, there are fine structures in the observed emission that require phase-coherent wave growth (e.g., Melrose 1986) rather than random-phase (maser) growth. Nevertheless, the maser theory accounts well for most qualitative properties and accounts semiquatitatively for the average properties. Evidently the average properties of a large number of localized, phase-coherent bursts may be described using maser theory.

This improving understanding of these other types of coherent emission has implications for our understanding of pulsar radio emission. A negative implication is that coherent emission in astrophysical plasmas is very highly structured in space, time and frequency, in ways that are not expected according to simple theories and that can even appear to be inconsistent with these theories. Nevertheless, a positive implication is that relatively simple theories, that combine a maser mechanism with some simple statistical ideas, can account for important average properties of the coherent emission.

6. Polarization

The importance of the polarization of any observed radio emission as a signature of its emission mechanism is well known. For pulsar radio emission the sweep of the linear polarization across the pulse window provided strong evidence for the standard polar cap model. However, as emphasized by Radhakrishnan (1992), there are other notable features of the polarization that should provide further insight but which are not adequately understood. Of particular importance in my opinion is the data on the polarization of individual pulses (e.g., Manchester, Taylor & Huguenin 1975; Stinebring et al. 1984; Xilouris et al. 1994). The data show subpulse structures which exhibit flips between orthogonal (generally elliptical) polarization. Flips between orthogonal elliptical polarizations seem to require highly specific conditions: a birefringent medium with elliptically polarized modes, an emission mechanism that produces a mixture of the two modes, and propagation conditions that cause the ray paths in the two modes to deviate sufficiently that they do not overlap strongly on reaching the Earth. A general theory is available for the wave properties in the exotic plasma expected to populate the pulsar magnetosphere (e.g., Arons & Barnard 1986). However, detailed modeling is needed.

7. Discussion

What should we expect of a theory for pulsar radio emission? It is clear that we cannot expect a theory of pulsar radio emission to be quantitative in the sense that the theory of synchrotron emission is quantitative. The foregoing remarks on other maser emission processes (plasma emission and ECME) suggest that our theories are likely to be useful only in describing the most general features of pulsar radio emission — the "climate" as opposed to the "weather." However, there are uncertainties and differences of opinion on what features of pulsar radio emission need to be explained by theory – the "climate" and the "weather" are not clearly distinguished.

One observational feature that is widely recognized as important is the polarization, particularly the flips in orthogonal polarization and the observation of these in single pulses. These are highly specific phenomena that will require a highly specific interpretation. As emphasized by Arons at this meeting, the escape of the radiation, including the effect of cyclotron absorption as well as of birefringence, is an important but inadequately understood aspect of the emission process. Any theory that can account satisfactorily for such flips in polarization will probably provide specific information on the emission mechanism, the source location and the plasma properties of the magnetosphere.

Whence the pulses? We are still unsure. There is strong evidence that at least some of the radio data is consistent with RFM and is strongly indicative of a ROP1 model. The most plausible emission mechanism in ROP1 models is some form of relativistic plasma emission, but linear acceleration emission and maser curvature emission are not ruled out. There is a strong, but still not compelling case, for operation of at least two different emission mechanisms, with one narrowband (ROP1 model) and the other broadband, with other qualitatively different properties, and perhaps indicating a ROP2 or a PPF model.

It may be that we will recognize the identification of the pulsar radio emission mechanism(s) only in hindsight. Rather like the "discovery" of the top quark, the experts of the day may simply agree that the mechanism has been identified as well as it ever will be.

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