Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Plasma Instabilities : Sources for Coherent Radio Emission

Estelle Asseo

Centre de Physique Théorique Ecole Polytechnique 91128 Palaiseau Cedex FRANCE

Abstract. The mechanism for the generation of pulsar radio emission has not yet been identified. Several coherent emission processes, linked to the motion of relativistic particles in the extremely strong pulsar magnetic field, have been proposed as possible candidates. Essential improvements, based on fundamental concepts of plasma physics, prove that collective plasma effects can provide the necessary degree of coherence. Progress in the 1990s, which is reported here, relates to curvature maser emission processes and relativistic plasma emission mechanisms.

1. Introduction

The nature of the coherent mechanism necessary to explain huge brightness temperatures associated with pulsar radio emissions is unknown. Several coherent radiation mechanisms have been studied.

Curvature radiation from relativistic particles moving in the extremely strong and curved pulsar magnetic field, appears to be a natural process. Both coherent curvature radiation from bunches of relativistic particles and coherent maser amplification of curvature radiation from relativistic particles issued from pair plasmas, have been discussed for a long time (Blandford 1975, Zheleznyakov, Shaposhnikov 1979, Shaposhnikov 1981, Chugunov & Shaposhnikov 1988). While the first process appears improbable, the conditions for maser amplification of the emission of relativistic particles moving along curved orbits are now clarified.

In the conditions specific to a coherent emission, bunches of relativistic monoenergetic particles should have very small dimensions as compared to the emitted wavelength. Such groups of particles, initially arranged to radiate in phase, are difficult to produce and to maintain in pulsar magnetospheres. As an example, spontaneous or induced velocity spread may lead to a suppression of the coherence itself (Ginzburg & Zheleznyakov 1975, Melrose 1978, 1992).

Otherwise, coherent maser amplification may result from curvature drift and/or field line torsion effects associated with the guiding center motion of a charged particle relativistically moving in the pulsar magnetic field. Linear theories proposed for such maser mechanisms involve randomly phased unstable electromagnetic waves, without any preliminary coherent behavior of particles or waves (Luo & Melrose 1992, 1995, Luo 1993, Luo et al. 1994).

Several plasma instabilities may also provide the required degree of coherence. Due to phase bunching of the particles associated with the instability

https://doi.org/10.1017/S0252921100041312 Published online by Cambridge University Press

mechanism, partial coherence appears spontaneously and may be further enhanced by the radiation process itself. This happens for the two-stream instability (Cheng & Ruderman 1977, Asseo et al. 1990, Asseo 1993), the cyclotron instability (Lominadze et al. 1983, Machabeli & Usov 1989, Kazbegi et al. 1991), the shear flow instability (Arons & Smith 1979) and for electromagnetic waves arising from linear acceleration of particles moving in intense electrostatic waves (Melrose 1978, Rowe 1995). This also occurs when electromagnetic waves, emitted by relativistic particles moving along a thin ring, enhance initial density modulations of the particle distribution. They produce a cascade process of amplification, referred to as radiative instability (Goldreich & Keeley 1971).

Linear theory of such plasma instabilities, adapted to relativistic pulsar plasmas of electrons and positrons, has been continuously explored. Recent improvements concern relativistic dispersion relations characterizing hot pulsar plasmas, detailed analysis of the distribution of particles in the pulsar magnetosphere, and the importance of boundaries in the emission region.

New developments using nonlinear plasma theory have been fruitful. Thus, study of nonlinear interactions between unstable waves implying scattering processes, provides estimates for conversion of these waves into observed radio radiation. A particular scattering effect, the emission of electromagnetic waves by particles which accelerate while moving in strong longitudinal waves, has been related to pulsar radio emission. Nonlinear studies of the evolution of instabilities, due to the development of strong turbulence, show the emergence of relativistic solitons forming elementary structures for pulsar radiation.

2. LINEAR THEORY

2.1. Curvature maser emission

Conditions for a coherent maser amplification of the curvature emission of relativistic electrons and positrons which form relativistic pair plasmas have been recently obtained using the "guiding center" approximation to describe the motion of particles. In this way, the slow variations of the pulsar magnetic field with the distance to the center of the neutron star are included. Particles in the strong pulsar magnetic field are constrained to the lowest Landau levels and thus to quasi one-dimensional motion, their transverse motion being extremely tight around field lines. The two necessary conditions obtained, $df/d\gamma > 0$ and $d\eta/d\gamma < 0$, respectively require a positive gradient of the distribution function and a negative derivative of the total emissivity relative to the energy. (Here f is the distribution function of particles, η is the total emissivity and γ the Lorentz factor). The first condition is associated with resonant particles and thus corresponds to a necessary inversion of the energy population. Both conditions can be simultaneously satisfied when curvature maser emission is due to curvature drift or when it is due to field line torsion.

If physical magnetospheric conditions are correctly described by polar cap models with dipolar magnetic fields, centrifugal acceleration is the driving force. Thus, curvature drift velocity and angle are associated with the guiding center of the particle motion. Subsequent maser amplification of the emission takes place at angles much larger than the drift angle, for frequencies much smaller than the gyrofrequency and is effective for high Lorentz factors $\gamma \approx 10^3 - 10^4$, drift

https://doi.org/10.1017/S0252921100041312 Published online by Cambridge University Press

effects being proportional to the particle energy. But such drift effects depend on the magnetic field strength and cannot satisfy at the same time observational constraints specific to slow or fast pulsars (Luo & Melrose 1992).

In reality, the pulsar magnetic field is probably non-dipolar, as suggested by some observations inconsistent with the dipolar assumption. Such a non-dipolar character is inevitable close to the surface of the star, due to multipolar contributions, and close to the light cylinder, due to field line distortion induced by rotation. In the simple case of locally helical field lines, maser amplification of the emission due to field line torsion arises close to the field line direction and is effective for relatively small Lorentz factors $\gamma \approx 10 - 40$, drift effects being inversely proportional to the particle energy. However, the drift angle is independent of the magnetic field strength and such drift effects can be significant for slow and fast pulsars (Luo 1993, Luo & Melrose 1995).

2.2. Importance of the curvature of magnetic field lines

Once curvature drift effects are included, it is possible to describe instabilities of the maser type, assuming vacuum-like dispersion properties, and hydrodynamic instabilities, assuming important plasma dispersion effects (Luo et al. 1994, Kazbegi et al. 1987). As implicit above, there is no maser action when curvature drift is negligible (Blandford 1975, Melrose 1978, Machabeli 1991). Thus, there is no maser action in the limit of an infinite magnetic field, the drift velocity being inversely proportional to the magnetic field strength. Similarly, a hydrodynamic instability vanishes at the limit of an infinite magnetic field, its growth rate being dependent on the drift velocity.

Such a result may solve the long controversy which has followed the introduction by Beskin et al. (1986, 1988) of specific "curvature modes", generated by plasma motion along curved field lines, as responsible for the generation of pulsar radio emissions (Larroche & Pellat 1987, Nambu 1989, Machabeli 1991). But contradictory statements, recently published, clearly show that no agreement has been reached (Istomin 1994, Gaelzer et al. 1995).

2.3. Beam - plasma instability in the pulsar magnetosphere

Polar cap models predict a relativistic primary beam ($\gamma_b \approx 10^7$) and a relativistic pair plasma ($\gamma_p \approx 10^2 - 10^3$) in the pulsar magnetosphere. For such beam and plasma flows, the ratio of plasma to gyro frequencies is much smaller than one, even beyond the light cylinder distance. Thus, plasma dispersion effects are dominant and the intense magnetic field only constrains flows to unidimensional motions. Classical treatments of these fluids in the cold plasma approximation only involve electrons and positrons of the pair plasma in a very efficient "beam-plasma" instability (Cheng & Ruderman 1977).

Electrons and positrons of the pair plasma are in fact hot and a relativistic treatment is necessary for a "beam-plasma" with both relativistic velocities and temperatures. Hydrodynamical and kinetic instabilities of plasma waves, related to resonance between waves and particles, can be deduced from appropriate relativistic dispersion relations (Magneville 1990). Analytic implications of this work in the simple case of hydrodynamical "beam-plasma" instability were proposed in Asseo (1993). Kinetic instabilities would predict higher growth rates and extended instability domains. Effectively, independent recent numerical analysis of a dispersion relation adequate to describe a "plasma" with relativistic temperature and a "beam" with nonrelativistic temperature, shows that the instability growth rate is non-zero and that the instability broadens towards large wavenumbers (Weatherhall 1994). Actual thermal effects do not stabilize the streaming instability. Thus, the two-stream instability should be significant in pulsar magnetospheres.

2.4. Repartition of charges in the pulsar magnetosphere

Lyubarskii (1992) analyses in detail the repartition of charges in a pulsar magnetosphere. Considering currents that flow along open magnetic field lines, return along the boundary between closed and open lines, and satisfy boundary conditions, he shows that there is a difference between current densities in the discharge region and in the pulsar magnetosphere. This implies an accumulation of charges in a very narrow region. Such collected charges generate a longitudinal electric field able to return particles to the surface of the star. The reverse flux of particles together with the main plasma flow result in a counterstreaming instability. If it is so, subsequent turbulent generation of plasma waves would be partially responsible for observed pulsar radio emissions. However, the true dynamical behavior of electrons and positrons forming the created pair plasma, in the gap region up to the pair production zone and beyond, should be examined carefully to ensure the existence of this screening region (Shibata 1996).

2.5. Boundary effects in the pulsar magnetosphere

Most plasma instabilities, studied for pulsar polar cap models, are derived in straight geometry assuming infinite and homogeneous primary beam and pair plasma. In view of the presumed pulsar magnetic field topology and of observations of pulsar profiles, which show a hollow cone or a full cone of radio emission, it seems natural to introduce curved geometry and the finite extent of the emission region. We thus describe relativistic flows in the pulsar magnetosphere as limited to the bundle of open dipolar magnetic field lines and bounded by external plasmas, the plasma on closed field lines and the plasma inside the hollow cone (Asseo et al. 1983, Larroche & Pellat 1987, Asseo 1995).

Our analysis shows that a "finite beam" instability may arise for a one component beam of relativistic particles, in addition to the radiative and two-stream instabilities. Excited unstable waves have such properties (growth rate, polarization, available electromagnetic energy), that they are most efficient close to the surface of the neutron star and may account for "core" emission, while two-stream (or radiative) instabilities are dominant further away and may be related to "conal" emissions. As originally proposed by Rankin (1990), several instability mechanisms may simultaneously act and be responsible for different features in radio profiles.

2.6. Model by Kazbegi, Lominadze, Machabeli, Melikidze

A high energy tail of electrons and positrons ($\gamma_t \approx 10^3 - 10^4$) may coexist in the pulsar magnetosphere with the primary beam ($\gamma_b \approx 10^6$) and pair plasma ($\gamma_p \approx 3 - 10$). Energy equipartition is presumed for these three populations.

Three types of waves exist in such a system of plasmas and beam, a purely transverse electromagnetic (t) wave and two electrostatic-electromagnetic high

https://doi.org/10.1017/S0252921100041312 Published online by Cambridge University Press

frequency (lt) waves, a superluminous wave, difficult to excite (lt1), and a subluminous wave (lt2) (Lominadze et al 1986). Different mechanisms, such as the anomalous Doppler effect due to cyclotron effects or Cerenkov resonance, may excite these waves. Indeed, for the plasma flows considered, gyro and plasma frequencies are comparable close to the light cylinder, so that resonance effects at the gyrofrequency do act.

The anomalous Doppler effect triggered by tail and/or beam energetic particles allows circularly polarized waves to be amplified within a very small domain of angles $\theta^2 < 2\delta$. Such a process would be responsible for typical observed "core" emission (Machabeli & Usov 1989, Kazbegi et al. 1991).

Cerenkov resonance from beam particles generates (t) or (lt) waves within a small angular domain, $\theta_1 < \theta < \theta_2$. This process would be related to observed "conal" emission. It is consistent with a 2-D cross-correlation analysis of individual pulses observed from PSR 1133+16 and may account for high correlations between the longitudes of the two components which form the mean double "conal" profile (Kazbegi, Machabeli, Melikidze and Smirnova 1993).

3. NONLINEAR THEORY

3.1. Nonlinear induced scattering effects

Nonlinear analysis for ultrarelativistic plasmas of electrons and positrons with characteristic one-dimensional properties in the strong pulsar magnetic field is necessary ultimately to describe pulsar radio waves.

Because only (lt) waves, that propagate at an angle to the magnetic field, may freely escape as electromagnetic waves in the pulsar magnetosphere, induced scattering effects should be significant only if there is a change in wave direction. In effect, strictly longitudinal waves are unable to emerge. Thus, transformation of longitudinal waves into longitudinal waves should not be considered any further. Recent estimates for the transformation of longitudinal waves into transverse waves due to induced wave scattering process, show that Thomson and transition scattering probabilities have comparably efficient scattering rates in a relativistic plasma (at least when the distribution functions of electrons and positrons differ) and lead to a nearly isotropic distribution of waves (Lyubarskii 1993). The relevance of such processes should be further explored.

Study of a similar scattering process is based on an analysis of the particle motion in strong longitudinal plasma waves that have an arbitrary phase velocity (Melrose 1978, Rowe 1992). One-dimensional relativistic particle motion and linear acceleration in such waves depend on the strength of the wave and on the total energy of the particles. In a luminous wave, particles can be phase locked and thus be continuously accelerated. In a superluminous wave, particles dragged by the wave, at the velocity (c^2/v_ϕ), are accelerated and may reach very high energies. By this means, a uniform distribution of monoenergetic particles, bunched at this particular velocity, triggers a characteristic coherent emission with a periodic train of pulses of infinitesimally short duration. Thus, strong coherent plasma waves cause particles to emit "coherent" radiation due to the acceleration they acquire in the wave. Numerically estimated and observed pulsar radio emission levels are comparable (Rowe 1995).

3.2. Strong turbulence effects

Physical effects associated with strong turbulence of Langmuir waves have been recently suggested as responsible for specific features of pulsar radio radiation. In a beam-plasma interaction, strong turbulence effects develop when wave-wave interactions begin to transfer energy out of resonance with the beam. The first stage is self modulational instability which creates localized wave packets. If the magnetic field is strong enough, such blocks contract and form stable soliton-like structures. If not, they collapse down to Debye scales being submitted to Landau dissipation and ultimately produce a high energy electron tail (Pelletier et al. 1988). While weak turbulence involves waves with random phases, strong turbulence in this way naturally introduces a high degree of coherence. In fact, the more rapid process will be dominant (Goldman 1984).

Modulational instability may be responsible for extremely rapid variations in non-thermal emissions. Indeed, nonlinear effects in a relativistic plasma of electrons and positrons induce low frequency density perturbations, superimposed over high frequency waves, which modulate the wave amplitude. Agreement is found for PSR 1133+16 (Gangadhara, Krishan, Shukla 1993).

The generation of soliton-like structures in strongly magnetized ultrarelativistic plasmas of the pulsar magnetosphere can be related to the formation of observed micropulses. Recent studies confirm that both linearly or circularly polarized waves can have a solitonic envelope (Khakimova & Tsytovich 1978, Chian & Kennel 1983, Mofiz & Mamun 1992,1993).

We suggest that a lattice of stable "Langmuir microstructures" should exist in the physical conditions of the pulsar magnetosphere. Such stable structures, to be related to Langmuir soliton-like plasma solutions, result from the nonlinear evolution of the relativistic two-stream instability (Asseo et al. 1990). Spatial and temporal features for these "microstructures" reproduce characteristics of observed micropulses in individual profiles. This description is realistic in view of experiments in a strongly magnetized plasma where a stable lattice of Langmuir solitons has been observed (Antipov et al. 1981).

Three typical radiation mechanisms are associated with such structures, namely (1) curvature radiation of the microstructures dragged along the dipolar pulsar magnetic field lines, (2) direct radiation of the microstructures themselves, (3) acceleration of beam particles in interaction with the lattice of Langmuir microstructures, extremely efficient when some coherence is maintained between the phases of beam particles, for instance due to a modulation of the beam. Only the two last mechanisms easily account for the high level of pulsar radio luminosities observed (Asseo 1993).

4. Conclusions

Maser curvature emission processes and relativistic plasma emission mechanisms in polar cap models are excellent presumed coherent sources for pulsar radio emissions. While consistency between maser processes predictions and observations needs further analysis, relativistic plasma instabilities might explain extreme values of brightness temperatures, radio frequency domain, "core" and/or "conal" features in averaged emission profiles and their main polarization features and formation of micropulses observed in individual profiles. As reviewed by Melrose in this volume, each mechanism is to be associated with one pulsar radio emission site. However, emitted electromagnetic waves leaving the pulsar magnetosphere might not reach observers, as mentioned by Machabeli and Arons during this colloquium. Only nonlinear plasma theory can determine whether sufficiently energetic waves could be transmitted to us. As an example, numerical modelling of observed micropulses may point to the generation emission mechanism (see the papers by Hankins and Weatherall in this volume).

Superb new observational results strongly prompt us to reconsider geometrical properties and plasma characteristics in pulsar emission regions. From these, different magnetic configurations, refraction, diffraction and propagation effects intrinsic to pulsar magnetospheres and properties of their deepest layers could be inferred (Arons, this volume). Thus, while nonlinear pulsar plasma physics needs more research, so does topology of pulsar magnetic fields (Krolik 1991, Ruderman 1991, Arons 1993), quantum plasma properties (Da Costa & Kahn 1991, 1995) and general relativity effects (Muslimov & Tsygan 1992), relevant close to the star. Nonpolar cap models may also matter (Krause-Polstorff & Michel 1985, Shibata & Mestel 1994, Ardavan 1994, Endean 1995).

References

Antipov, S.V. Nezlin, M.V. Trubnikov, A.S. 1981, Physica 3D, 1 and 2, 311
Ardavan, H. 1994, MNRAS, 268, 361
Arons, J. 1993, ApJ, 408, 160
Arons, J. Smith, D.F. 1979, ApJ, 229, 728
Asseo, E. Pellat, R. Sol, H. 1983, ApJ, 266, 201
Asseo, E. Pelletier, G. Sol, H. 1990, MNRAS, 247, 529
Asseo, E. 1993, MNRAS, 264, 940
Asseo, E. 1995, MNRAS, 276, 74
Beskin, V.S. Gurevich, A.V. Istomin, Ya.N. 1986, Sov. Phys. Usp., 29, 946
Beskin, V.S. Gurevich, A.V. Istomin, Ya.N. 1988, Ap&SS, 146, 205
Blandford, R.D 1975, MNRAS,170, 551
Cheng, A.F. Ruderman, M.A. 1977, ApJ, 212, 800
Chian, A. C.L. Kennel, C.F. 1983, Ap&SS, 97, 8
Chugunov, Yu.V. Shaposhnikov, V.E. 1988, Astrofizika, 28, 169
Da Costa, A.A. Kahn, F.D. 1991, MNRAS, 251, 681
Da Costa, A.A. Kahn, F.D. 1995, MNRAS, submitted
Endean, G. 1995, MNRAS, 275, 309
Gaezler, R. Schneider, R.S. Ziebell, L.F. 1995, Phys. Rev. E , 51, 2407
Gangadhara, R.T. Krishan, V. Shukla, P.K. 1993, MNRAS, 262,151
Ginzburg, V.L Zhelezniakov, V.V 1975, ARA&A, 13, 571
Goldman, M. V. 1984, Rev. Mod. phys., 56, 709
Goldreich, P. Keeley, D.A. 1971, ApJ, 170, 463
Istomin, Ya.N. 1994, Plasma Phys. Contr. Fus., 36, 1081
Kazbegi, A.Z. Machabeli, G.Z. Melikidze, G.I. 1987, Aust. J. Phys., 40, 755

Kazbegi, A.Z. Machabeli, G.Z. Melikidze, G.I. 1991, MNRAS, 253, 377

Kazbegi, A.Z. Machabeli, G.Z. Melikidze, G.I. Smirnova, T.V. 1993, Astrofizika, 34, 433

Khakimova, M. Tsytovich, V.N. 1978, Radiofizika, 21, 621

Krause-Polstorff, J. Michel, F.C. 1985, MNRAS, 213, 43p

Krolik, J.H. 1991, ApJ, 373, L69

Larroche, O. Pellat, R. 1987, Phys.Rev.Lett, 59, 1104

Lominadze, Dzh. G. Machabeli, G.Z. Usov, V.V. 1983, Ap&SS, 90, 19

Lominadze, Dzh. G. Machabeli, G.Z. Melikidze, G.I.Pataraya, A.D 1986, Sov. J. Plasma Phys., 12, 712

Luo, Q. 1993, Proc. ASA, 10(3), 258

Luo, Q. Melrose, D.B 1992, MNRAS, 258, 616

Luo, Q. Melrose, D.B Machabeli, G.Z 1994, MNRAS, 268, 159

Luo, Q. Melrose, D.B 1995, MNRAS, 276, 372

Lyubarskii, Yu.E. 1992, A&A, 261, 544

Lyubarskii, Yu.E 1993, Sov. Astr. Lett., 19, 208

Machabeli, G.Z. 1991, Plasma Phys. Contr. Fus., 33, 1227

Machabeli, G.Z. Usov, V.V. 1989, Sov. Astr. Lett., 15, 393

Magneville, A. 1990, J. Plasma Physics, 44, 191 and 44, 213

Melrose, D.B 1978, ApJ, 225, 557

Melrose, D.B in Hankins, T.H. Rankin, J.M. Gil, J.A. editors 1992, Proceedings IAU Symposium 128 "The magnetospheric structure and emission mechanisms of radio pulsars", Pedagogical University Press, Zielona Gora, Poland, p. 306

Mofiz, U.A. Mamun, A.A. 1992, Phys.Fluids B, 4, 3806 and 1993, 5, 1667

Muslimov, A.G. Tsygan, A.I. 1992, MNRAS, 255, 61

Nambu, M. 1989, Plasma Phys. Contr. Fus., 31, 143

Pelletier, G. Sol, H. Asseo, E. 1988, Phys.Rev.A, 38, 2552

Rankin, J.M. 1990, ApJ, 352, 258

Rowe, E.T. 1995, A&A, 269, 275

Rowe, E.T. 1992, Aust.J.Phys., 45, 1 and 45, 21

Ruderman, M. 1991, ApJ, 366, 261 and 1991, ApJ, 382, 576

Shaposhnikov, V.E Astrofizika 1981, 17, 749

Shibata, S. 1996, these proceedings

Shibata, S. Mestel, L. 1994, MNRAS, 269, 191

Weatherall, J. C. 1994, ApJ, 428, 261

Zheleznyakov, V.V Shaposhnikov, V.E 1979, Aust. J.Phys., 32, 49