THEORETICAL ASPECTS OF COHERENT RADIO-EMISSIONS IN NATURE: THE PULSAR EXAMPLE*

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Abstract. In this short review we first comment generally about natural Radio-emissions in the solar system and then emphasize recent theoretical results concerning Pulsars.

1. Introduction

In the solar system we can make local measurements of particles and fields which allow a detailed and direct understanding of the observed phenomena. Radio emissions in the solar wind are generally produced by beams of energetic electrons of solar origin flowing through the interplanetary plasma. 'Auroral' beams make planetary emissions. These beams can be accelerated by 'reconnection processes', which follow changes in the magnetic field topology at the surface of the Sun, or by solar wind interaction with magnetospheric boundaries. The beams can also be produced by 'dynamo effects' inside the planetary magnetospheres: the motion of Io across the Jovian magnetic field induces, by closure of the electric circuit, a drop of potential along field lines. Plasma convection across the terrestrial dipole field implies perpendicular electric currents. Following solar wind perturbations, when these currents are no longer divergence free, field aligned currents carried by electrons are necessary.

Apart from their origin, radio emissions usually† have another common feature, a brightness temperature much higher than the energies of the particles supposed responsible for the emission. That fact, puzzling with respect with Planck's law, is now understood as being associated with 'coherent processes' - 'maser Mechanisms'. We comment later upon these 'magic' words.

2. General Comments About Natural Radio-Emissions

Let us give some details about the parameters pertinent to the most well-known coherent radio emissions.

† When we say 'usually', we are aware of the decimetric emissions from the Jovian belts. These emissions are produced by synchrotron mechanisms and have a temperature of brightness in agreement with the MeV electrons trapped and measured by Pioneer 10 and 11 in the Jovian belts. They gave the correct order of magnitude of the Jovian dipole field. Synchrotron emissions are fundamental in our understanding of astrophysical objects but will not be discussed in our talk.
In the solar wind one observes type III radio bursts, produced by electron beams with an energy in the ten kilovolt range. Probes have measured the local distribution function of ‘type III electrons’ and proved their qualitative association with locally generated radio bursts with frequency around the plasma frequency, (some tens of kilocycles in the Earth’s vicinity).

Planetary radio emissions have decametric wavelengths for Jupiter, hectometric for Saturn and kilometric for the Earth. In the terrestrial case, auroral field aligned currents are carried by electrons in the kilovolt range; they have been measured by particle detectors aboard rockets and satellites and are clearly associated with kilometric radiation. A similar association is not yet established for Jupiter; the electrons are usually taken as more energetic – tens or even hundreds of kilovolts.

Pulsar radio emissions (in the frequency range of $10^8$–$10^9$ cycles s$^{-1}$) are the basis for the discovery of fast rotating neutron stars. They are also theoretically associated with highly relativistic beams of electrons (and positrons?) flowing along a Pulsar’s magnetic field lines. It is interesting to realize that these beams seem now a consequence of the coupling of a fast rotating object with plasma it generates itself.

If we try to be more precise about the parameters relevant to theoretical analysis, we find many important differences between the above cases. The solar wind plasma is mainly unmagnetised (the plasma frequency $f_{pe}$ is much larger than the electron cyclotron frequency $f_{ce}$). Planetary plasmas are highly magnetised: $f_{pe} \approx f_{ce}$ in the terrestrial magnetosphere; $f_{ce} \gg f_{pe}$ in the Jovian ionsphere. Close to the surface of a neutron star, the magnetic field can be taken as infinite for any theory of radio emissions. The broad range of particle energies from non relativistic to highly relativistic and such differences in plasma parameters of course lead to apparently unconnected theories. (It is in fact a usual feature of theoretical papers to emphasize subtleties rather than similarities). Nevertheless let us now discuss what needs to be understood about the ‘magic’ word of coherence*, a word used in theories of all the above phenomena.

2.1. COHERENCE OF RADIO EMISSIONS

The quoted emissions have in common high brightness temperatures: $10^{16}$ degrees for the Earth and Jupiter, up to $10^{30}$ for Pulsars. By high we mean that such temperatures cannot be explained by the black body radiation of a plasma with the same temperature or by particles of that energy. In all cases orders of magnitude are missing. Since black-body radiation is incoherent, theoreticians have been, in a quite natural way, looking for coherent mechanisms. To be more precise, the idea is to take an individual radiation mechanism (Cerenkov, synchrotron curvature in the Pulsar case) and then try to organize the particle population in space and time in ‘artificial’ antennas. The total electric field $\mathbf{E}$ is then the sum of individual contributions:

$$\mathbf{E} = \sum_i E_i \exp i\phi_i.$$

*[The word coherence is taken here for radio emissions produced in continuous media. Maser mechanisms of molecular origin as those relevant for interstellar matter are not considered.]