V. JOVIAN RADIO BURSTS AND PULSARS

(Edited by F. G. Smith)

Organizing Committee

F. G. Smith (Chairman), M. M. Komesaroff, V. K. Prokof'ev, M. J. Rees, B. Warner

SUMMARY

Professor G. R. A. Ellis reviewed the wide range of radio emission from Jupiter. At centimetric wavelengths the thermal radiation corresponds to a blackbody at 130K. Between 2 m and 10 cm wavelength there is a powerful component of synchrotron radiation from the electrons trapped in the radiation belts. At longer wavelengths there is a great variety of impulsive radio emission from coherent plasma oscillations.

The magnetic field of Jupiter is known from the polarisation of the synchrotron radiation to be situated centrally (within one tenth of the radius) and inclined at 10° to the rotation axis. The radiating electrons have energies of the order of 10 MeV, and a density of 10^{-3} cm^{-3}, much greater than in the case of the Earth's radiation belts.

The decametric radiation varies with the rotation of Jupiter, possibly analogously to pulsar radiation. Bursts at around 4 MHz reach very high brightness temperatures, exceeding 10^{17} K. The occurrence of these strong bursts is closely related to the position of the Jovian satellite Io, which must have an interaction with the main magnetic field.

The bursts are usually almost completely circularly polarised, varying in detail with radio frequency. There are many different time scales of fluctuation, from hours to microseconds: again this is reminiscent of pulsar radiation. The bursts drift rapidly in frequency, as in some types of solar radio bursts. The drift rate takes characteristic values at different frequencies. Drifts can occur both upward and downward in frequency.

Jovian radio bursts may be closely related to some radio emission from the terrestrial ionosphere, such as the 'hiss', 'dawn chorus', and 'whistlers'. These are stimulated by energetic particles from the Sun. Artificial stimulation by terrestrial radio sources has also been deomonstrated.

Prof. Ellis gave a brief review of the theory of Jovian radio bursts, and referred the audience to the following key references:

References

Carr, T. D. and Gulkis, S.: 1969, *Ann. Rev. Astron. Astrophys.* 7, 577.
Ellis, G. R. A.: 1965, *Radio Sci.* **69D**, 1513.
Goldreich, P. and Lynden-Bell, D.: 1969, *Astrophys. J.* **156**, 59.

Dr J. Ables presented a review of the radio observations of pulsars, concentrating on those observations which are particularly important in understanding the radiation mechanism.

The radio pulses may be described by an integrated pulse envelope extending over a few percent of the period, obtained by the superposition of some hundreds of pulses.

Contopoulos (ed.), Highlights of Astronomy, 493–498. *All Rights Reserved*

Individual pulses contain narrower components known as subpulses; these may contain variations on a shorter timescale, known as the microstructure. The subpulses often appear at steadily changing times in successive pulses, so that they 'drift' through the integrated pulse profile. In some cases, the drifting occurs clearly at the beginning and end of the profile, but not at the centre.

The pulse energy is very variable from pulse to pulse. The statistical distribution of energy in the Crab Pulsar may be consistent with Poisson statistics, in which pulses are made up of a randomly varying number of individual spikes. There are also random variations in intensity on timescales of months and years. The radio spectral index is generally between -1 and -3.5, but it often becomes even steeper at the highest radio frequencies, and also becomes flatter or reverses in slope at low frequencies.

The polarisation of the radio pulses gives an important clue to the radiation process. Integrated profiles may be made by adding the Stokes parameters of a sequence of pulses. These integrated profiles show polarisation which is predominantly linear, often with a monotonic swing of position angle by up to 180°. A circularly polarised component is also seen for some pulsars near the centre of the integrated profile.

The degree of polarisation generally falls at higher radio frequencies. The subpulses are typically very highly polarised, showing changing forms of elliptical polarisation within each subpulse as it drifts.

Theories of the radiation mechanism fall into three classes according to the location of the emitting region. The pulsar is a rotating neutron star, with a strong magnetic field which forces any ionised magnetosphere into co-rotation with the star. The three classes of theory refer to an origin in a magnetic polar region close to the surface, or in a region close to the velocity of light cylinder where co-rotation would produce speeds approaching the speed of light, or further out beyond the velocity of light cylinder.

The polar cap theories involve a radiation mechanism (curvature radiation) which beams radiation along the polar magnetic field lines. They provide in particular an explanation of the absence of 'interpulses' in most pulsars, since the radiation from the opposite pole is not observed unless the angle between the magnetic and rotation axes is near 90°. The 'velocity of light cylinder' theories are derived from the observed independence of pulse width on frequency. The width is determined by geometrical considerations only, through relativistic beaming.

A third theory, proposed by Lerche, involves a source beyond the velocity of light cylinder which is excited by the anisotropic magnetic pressure of the rotating field.

Prof. P. A. Sturrock gave an account of the 'polar-cap' model, following the lines of an early article (P. A. Sturrock, *Astrophys. J.* **164**, 529, 1971), modified in accordance with a more recent article (D. H. Roberts and P. A. Sturrock, *Astrophys. J.* **181**, 161, 1973).

Intense electric fields develop near the magnetic polar caps which accelerate both ions and electrons to high energies. The electrons radiate high-energy gamma rays which may annihilate in the magnetic field to produce electron-positron pairs. If this occurs, the flow becomes unstable, giving rise to bunching and coherent radio emission. If the transition from closed to open field lines occurs at the 'force-balance radius', rather than the light cylinder, one obtains good agreement with the observed braking index, pulse widths, and period-age distribution. The pair production cascade also explains the high particle flux from the Crab pulsar into the nebula. X-ray radiation is attributed to synchrotron radiation from the secondary electrons and positrons, but the optical radiation is believed to be due to coherent radiation from the electron-positron bunches resulting from the cascade as these bunches moved along the curved magnetic field lines.

Prof. F. G. Smith showed that the relativistic beaming theory resulted from a more detailed study of the observed characteristics of the pulses, and particularly of the width and polarisation of the sub-pulses. The emitting region appeared to be situated typically at 0.7 to 0.9 of the radial distance to the velocity of light circle, and located in a particular region of the magnetic field pattern. The radiation mechanism appeared to be coherent cyclotron radiation, in which bunches of high-energy electrons moved in approximately circular orbits. This would be narrow-band radiation; the wide spectrum must be generated by an assembly of such sources. Optical and X-ray radiation from the Crab Pulsar would then be incoherent synchrotron radiation from the same particles.

DISCUSSION

In a general discussion the following points offered possibilities of distinguishing between the theories:

Cole: The maintenance of sub-pulse structure over many pulsar rotations must be explained as a long-lived moving electron configuration.

Rees: The fine frequency structure from narrowband sources might appear differently across a relativistically compressed pulse, due to the varying Doppler effect.

Ables: The lack of an interpulse in most pulsars is difficult to explain by the relativistic beaming model for co-rotating sources since it implies only a single such emitting region. If emitting regions are associated with magnetic poles, it is necessary to explain why this theory would not predict at least two pulses per rotation.

Lyne: The smooth and very rapid changes of polarisation within the sub-pulses favours the theory of beam compression.

Komesaroff: On Professor Smith's model the cyclotron frequency is emitted. This being longitude dependent would result in a relative delay of different frequencies which is not observed.

Sturrock: Estimates of the particle flux from the pulsar into the Crab nebula, of 10^{41} electrons or positrons per second, seem not to be compatible with the model proposed by Smith. Also, Smith's estimate of the magnetic field strengths required by long period pulsars leads to estimates of the 'age' which are much shorter than those found observationally.

Smith: The two theories approach the problems in different ways. Although the relativistic beaming theory does not attempt to explain the plasma physics, it is directly related to the observations and provides a description of the location and nature of the emitter which seems to be inescapable. The model involving flat sheets of charge cannot match the detailed description of the pulse structure.

Sturrock: I agree that the earlier model involving flat sheets of charge is incompatible with observational data. It now seems that the current pattern at the polar caps must have highly variable small-scale structure.

Prof. F. D. Kahn discussed the propagation of the electromagnetic wave associated with pulsar rotation. According to some theories a pulsar emits most of its energy in the form of very low frequency electromagnetic waves. The period of such a wave is the same as that of the pulsar. Its amplitude can be very large indeed: for example, in the case of the Crab pulsar, the vector potential would have a magnitude A of order 10^{14} (in Gaussian units) at the speed of light cylinder. In the presence of such a wave an electron or a proton will have a mass of order $eA/c^2 = 5 \times 10^{-17}$ gm. This is several orders of magnitude larger than the rest mass of either particle. The transmission of the vlf waves through a plasma therefore depends very much on their amplitude, and simple propagation properties can be expected only for circularly polarized waves with a single frequency.

Various interesting suggestions have been made about the manner in which vlf waves actually force their way through a diffuse plasma. One notable proposal, due to Rees, is that the waves clear channels for themselves through the plasma, within which their vector potential is large enough and along which they can propagate.

But in order to be able to use any such theory one needs to know whether a vlf wave of pure frequency is stable. Just recently a stability calculation has in fact been undertaken (Claire Ellen Max, 1973, preprint). It is found that a circularly polarised wave of large amplitude, with a given frequency and wavenumber, is unstable to a break-up into circularly polarised waves of neighbouring frequencies and wavenumbers. So far only a linearized calculation is available. But the probable inference is that no circularly polarised wave of pure frequency can continue to propagate. Instead it will break up into a mixture of waves with different frequencies and different handedness of polarisation. The mass eA/c^2 of the charged particles will then fluctuate rapidly, and this will cause equally rapid changes in the refractive index of the medium for waves of any frequency. The propagation of any wave will therefore be impeded. Very probably the energy of vlf wave is thus converted into random energy of the charged particles quite close to the source of the radiation.

Prof. L. Mestel presented the theory of Force-Free Pulsar Magnetospheres.

The standard model of an obliquely rotating neutron star is adopted for the pulsar: the aim is to formulate and solve the equations to the structure of the external magnetic field and associated electric field. Since only a small fraction of the rotational energy being lost from the Crab pulsar is tapped to supply the radio, X-ray and optical pulses, it is a plausible approximation to ignore such losses and treat the magnetospheric field as simply coupling the pulsar with the surrounding nebula *via* the light-cylinder. The theory should predict a breaking index; it could also conceivably shed light on the pulsar radiation mechanism, e.g. if the field could be shown necessarily to have current singularities.

The field is assumed steady in the rotating frame, so that

$$\frac{\partial}{\partial t} = -\Omega \frac{\partial}{\partial \theta}, \tag{1}$$

where $\Omega\mathbf{k}$ is the angular velocity vector and θ the azimuthal angle about $\mathbf{k}$. The postulate that the star is surrounded by a strict vacuum – with zero charge-current density – then yields the classical Maxwell-Deutsch wave of frequency Ω, discussed e.g. by

Pacini (1967, 1968) and Ostriker and Gunn (1969). Well within the light-cylinder this wave has an electric field component $\mathbf{E}_{\|}$ along $\mathbf{B}$ of the same order as $\mathbf{E}_{\perp}$, and this can act as a powerful accelerator on individual charges. However, in the presence of a very small plasma density, the component $\mathbf{E}_{\|}$ causes a charge-separation which is likely to reduce $|\mathbf{E}_{\|}|$ to a value much below $|\mathbf{E}_{\perp}|$. To a first approximation, the vacuum conditions $\varrho_e = 0, j = 0$, are now replaced by the plasma condition

$$\mathbf{E} + \frac{(\Omega\mathbf{k} \times \mathbf{r}) \times \mathbf{B}}{c} = 0, \tag{2}$$

this being equivalent to the more general $\mathbf{E} + (\mathbf{v} \times \mathbf{B})/c = 0$ when the velocity $\mathbf{v}$ is the sum of the co-rotation velocity $\Omega\mathbf{k} \times \mathbf{r}$ plus a component parallel to $\mathbf{B}$. (For (2) to hold beyond the light-cylinder we require that the velocity components along the field-lines are directed so as to keep the total velocity below c). Associated with $\mathbf{E}$ from (2) is the charge density

$$\varrho_e = \frac{\nabla \cdot \mathbf{E}}{4\pi} = - \frac{\Omega\mathbf{k}}{2\pi c} \cdot \{\mathbf{B} - \tfrac{1}{2}\mathbf{r} \times (\nabla \times \mathbf{B})\}. \tag{3}$$

Goldreich and Julian (1969) argued that the pulsar itself would supply the plasma: $\mathbf{E}_{\|}$ acting at the pulsar surface would extract charges of one sign or the other. Ruderman (1971) estimated that the work-function resisting electronic emission is quite modest, but that ions would probably remain bound, implying that any currents into and out of the pulsar probably consist of electrons only. We postulate that at each point where Equation (3) requires ϱ_e to be positive, the magnetosphere has in fact acquired a sufficient ion density (e.g. via accretion). A strictly *charge-separated* magnetosphere is not consistent with the steady-state condition (Goldreich and Julian, 1969; Okamoto, 1973); however, even if the net charge-density is a good deal smaller than the density of either sign, the associated mass-density ϱ is still extremely small, in the sense that $B^2/8\pi\varrho c^2 \gg 1$ (Mestel, 1971). The equations of motion of the plasma then reduce to the *relativistic force-free condition*

$$0 = 4\pi\varrho_e\mathbf{E} + \frac{4\pi\mathbf{j}}{c} \times \mathbf{B} = (\nabla\mathbf{E})\,\mathbf{E} + \left(\nabla \times \mathbf{B} - \frac{1}{2}\frac{\partial \mathbf{E}}{\partial t}\right) \times \mathbf{B}. \tag{4}$$

(The vacuum solutions are clearly a sub-class, in which the two terms in (4) vanish separately). Equations (2), (3) and (4) and condition (1) jointly yield (Mestel, 1973; Endean, 1973)

$$\nabla \times \tilde{\mathbf{B}} = \psi\mathbf{B}, \qquad \mathbf{B} \cdot \nabla\psi = 0, \tag{5}$$

where

$$\tilde{\mathbf{B}} = \left\{B_r\left(1 - \frac{\Omega^2 r^2}{c^2}\right), B_\theta, B_2\left(1 - \frac{\Omega^2 r^2}{c^2}\right)\right\} \tag{6}$$

in cylindrical polar coordinates (v, θ, z). Equations (5) are generalizations – to non-axially symmetric systems that are steady in the rotating frame – of the axisymmetric equations given by Michel (1973) and Scharlemann and Wagoner (1973).

The adoption of the 'magnetohydrodynamic approximation' (2) does *not* imply at all that $\mathbf{E}_{\|}$ is assumed to be strictly zero, so that electrical acceleration parallel to **B** is ruled out. For the solutions of Equations (5) to be the zero-order terms in a self-consistent iterative scheme, we merely require $|\mathbf{E}_{\|}| \ll |\mathbf{E}_{\perp}| \simeq \Omega rB/c$. There will in general be currents flowing parallel to **B**, and $\mathbf{E}_{\|}$ can be found from the component along **B** of the equation of motion of the electrons. The approximation (2) for constructing a zero-order field model is justified if $|\mathbf{E}_{\|}|$ so determined is much below $|\mathbf{E}_{\perp}|$. The most important correction to (2) may very well come not from the relativistic inertial terms near the light-cylinder but from resistance due to two-steam instability. The essential point is that $\mathbf{E}_{\|}$ – so important in theories of radio emission such as Prof. Sturrock's – should be *determined* rather than settled by 'fiat' (Ruderman, 1972).

Well within the light-cylinder ($r \ll r_c = c/\Omega$), Equations (5) can be approximated by the curl-free condition, whereas when $r \simeq r_c$ both particle and displacement currents are significant. When $r \gg r_c$ only the displacement current is important, so that for those field-lines which get beyond r_c the wave is essentially a Maxwell vacuum wave. A crucial question, which solution of Equation (5) will answer, is: how much magnetic flux will pass through the singularity at r_c? For the only simple case – cylindrical symmetry, with $\partial/\partial z = 0$, but $B_z \neq 0$ – the answer is rather dramatic: all the field-lines leaving the pulsar are trapped within r_c, yielding a zero radial Poynting vector at r_c. Thus the presence of the charge density (3) kills the cylindrical wave that would otherwise carry energy to infinity.

This result cannot be generalized to more realistic geometry, but it is plausible that the field structure near the light-cylinder will usually be significantly affected by the particle current. As noted by Dr Claire Max (private communication), there is a partial similarity between the pulsar magnetosphere problem and that of the propagation of *plane* strong waves in dense plasmas. The critical electron density for such waves to be stifled is comparable with the charge density (3) at the light-cylinder. It is therefore not surprising that the pulsar wave is killed in one simple geometry, and that it will probably be significantly modified in general. Further results – in particular, the prediction of a braking index – must await solution of Equations (5).

References

Endean, V. G.: 1973, *Astrophys. J.*, in press.
Goldreich, P. and Julian, W. H.: 1969, *Astrophys. J.* **157**, 869.
Mestel, L.: 1971, *Nature Phys. Sci.* **233**, 149.
Mestel, L.: 1973, *Astrophys. Space Sci.* **24**, 289.
Michel, F. C.: 1973, *Astrophys. J.* **180**, L133.
Okamoto, I.: 1973, in preparation.
Ostriker, J. P. and Gunn, J. E.: 1969, *Astrophys. J.* **157**, 1395.
Pacini, F.: 1967, *Nature* **216**, 567.
Pacini, F.: 1968, *Nature* **219**, 145.
Ruderman, M.: 1971, *Phys. Rev. Letters* **27**, 1306.
Ruderman, M.: 1972, *Ann. Rev. Astron. Astrophys.* **10**, 427.
Scharemann, E. T. and Wagoner, R. V.: 1973, *Astrophys. J.* **182**, 951.