PULSAR OPTICAL EMISSION AS AMPLIFIED SYNCHROTRON EMISSION

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Pulsed optical emission has been observed from the Crab and Vela pulsars (Manchester and Taylor 1977). The pulse profile of the Crab pulsar has a main pulse and a strong interpulse separated by about 40% of the pulsar period; the peak of the main pulse is just resolved at 20 μs resolution; the spectrum is peaked at about $10^{14.8}$ Hz; the pulse profile is constant over long time intervals; both the main pulse and the interpulse are strongly linearly polarized with position angle varying smoothly through each profile and with a minimum of polarization near each peak; the pulses are not significantly circularly polarized. A number of models have been proposed to explain the optical emission from the Crab pulsar but none is completely satisfactory. The spectral peak is too low for incoherent synchrotron emission, the pulse profile is too constant for inverse Compton scattering of radio emission and the similarity with the low-energy X-ray emission argues against coherent curvature emission.

A model to interpret the properties of the optical emission from the Crab pulsar in terms of anisotropic relativistic particles in a charge-neutral electron-positron plasma emitting amplified synchrotron radiation in a hollow cone above one polar cap of the pulsar is presented here. Synchrotron emission <u>in vacuo</u> cannot be amplified but amplified emission (by the laser process) can occur in the presence of a plasma (McCray 1966, Zheleznyakov 1967). Synchrotron emission by a monoenergetic stream of electrons (Lorentz factor γ) all with the same pitch angle in a cold magnetoactive plasma has been studied by Fung (1969) for frequencies ω much greater than either the electron plasma frequency $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ or the nonrelativistic electron gyrofrequency $\Omega_e = eB/m_e c$. Zheleznyakov and Suvorov (1972) have pointed out that Fung's analysis is only valid when one of the natural modes of the plasma is polarized in the sense studied by Fung (i.e. linear polarization in the direction perpendicular to both the magnetic field B and the wave propagation vector $\underset{\sim}{k}$). The results of Fung therefore apply for a charge-neutral electron-positron plasma for which the natural modes of propagation are linearly polarized for all directions of propagation (Melrose and Stoneham 1977). For emission into a cold charge-neutral

W. Sieber and R. Wielebinski (eds.), Pulsars, 235–238.

electron-positron plasma streaming with Lorentz factor γ_p along the magnetic field lines, ω_p in the formulae of Fung (1969) must be interpreted as $(8\pi n_e e^2/m_e \gamma_p)^{1/2}$, with n_e equal to the electron number density in the plasma frame. Fung's results are then valid for frequencies $\omega >> \omega_p, \Omega_e/\gamma_p$ for which the refractive index of the plasma is approximately $\mu = 1 - \omega_p^2/2\omega^2$ for both natural modes of propagation.

The dynamical models of Ruderman and Sutherland (1975) and Arons and Scharlemann (1979) suggest that a dense electron-positron plasma is produced above at least one polar cap of a pulsar. The plasma streams outward at relativistic velocity along the open field lines of the approximately dipolar magnetic field and is permeated by a faster moving beam of monoenergetic electrons or positrons. The particle motion is essentially one-dimensional throughout most of the pulsar magnetosphere since the synchrotron lifetime is very much shorter than the transit time. To follow the field lines, however, the particles drift in the direction of the binormal. For ultrarelativistic electrons or positrons this drift velocity is $v_d = \gamma c^2/\Omega_e \phi$, where ϕ is the local radius of curvature, and the angle between the particle velocity and the magnetic field is $\psi = v_d/c = \gamma c/\Omega_e \phi$ when $v_d << c$. The particles will gain non-zero pitch angles if ϕ changes on a timescale much shorter than the synchrotron lifetime. This can happen for particles emitted by the Crab pulsar if the energy density of the particles exceeds the energy density of the pulsar magnetic field within the light cylinder of the pulsar. The particles are then no longer forced to follow curved field lines and their pitch angles become of order ψ. The most energetic particles on the open field lines farthest from the magnetic dipole axis gain the largest pitch angles and, for reasonable pulsar parameters, emit amplified synchrotron radiation peaked at optical frequencies in a hollow cone about the magnetic dipole axis. High optical luminosity results from the optical depth for the amplified radiation being very much greater than unity.

The optical emission mechanism proposed here is consistent with the single pole interpretation of interpulses proposed by Manchester and Lyne (1977). The angular size of the emission region is small enough to give a sharp peak to the main optical pulse but is much greater than the angular size of an individual synchrotron laser (which has an opening angle of order ψ) so there is little temporal fluctuation in the optical emission if the flux of particles from the pulsar is suitably constant. The emission from an individual laser will be linearly polarized because emission into one natural mode of the electron-positron plasma is favoured over emission into the other mode. Emission from the incoherent collection of lasers, however, would be depolarized if the field structure was purely poloidal, but the presence of a toroidal component to the field gives a polarization curve which has a maximum in the pulse wings and a minimum near each pulse peak (Elitzur 1979).

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DISCUSSION

KAHN: Do you need to have a high energy plasma beam and a low energy background plasma, or could you achieve the same result with a more continuous energy distribution?

STONEHAM: The synchrotron maser operates for any distribution of particle energies provided there are some highly relativistic particles and the refractive index of the system is less than unity. For the maser to be significant, however, the optical depth of the emission must be negative with magnitude greater than unity.

ARONS: Can you comment on the changes in the magnetic field required to break the adiabatic invariants and allow centrifugal force to excite the gyrational motion? Do you see these changes as plausible, given the lack of fluctuations in the optical pulse-intensity profile?

STONEHAM: The magnetic field direction must change in such a way that $\psi = v_d/c$ changes by an angle greater than the beamwidth of the emission on a timescale shorter than the synchrotron timescale. Such a small change in field direction is likely to occur closer to the pulsar surface than major changes in the magnetic field structure due to finite particle inertia.

KUNDT: How large is your coherence factor? Aren't you worried by the smallness of intensity fluctuations (being smaller than 1% from pulse to pulse)?

STONEHAM: The optical depth for th amplified emission is of the order 10. The smallness of the intensity fluctuations is due to the extremely small size of each individual synchrotron laser together with the smallness of the temporal variation in the flux of particles from the pulsar.

F.G. SMITH: What sharpness did you assume for the peak of the profile? The published peak is about 300 microseconds wide.

STONEHAM: The sharpness of the peak in the optical emission profile was used to estimate the pitch angles and Lorentz factors of the emitting particles and to obtain a lower limit on the peak frequency for incoherent synchrotron emission by particles within the light cylinder of the Crab pulsar. Even with a profile sharpness of 300 μs it is difficult to obtain incoherent synchrotron radiation peaked at $10^{14.8}$ Hz from relativistic particles with a spread in pitch angle and Lorentz factor.