(about six) have been confirmed. Two have already been described[2], and others may yet be found.

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Coherent Synchrotron Emission in the Crab Nebula

RECENT analyses of the electrodynamics of the plasma surrounding a rotating magnetic neutron star[1–3] have provided plausible mechanisms for the acceleration of high energy particles in the Crab Nebula. We shall discuss some implications of these models, but the results may apply to a variety of models of the interaction between a central object and a surrounding nebula. In particular, we propose an explanation of the low frequency radio source of small diameter[4], which probably lies near the centre of the Crab[5] and which may therefore be associated with the pulsar. Specifically, we suggest that the high brightness temperatures associated with this source[6] may result from coherent synchrotron emission associated with phase-coherence of the electron gyromotion.

Low energy electrons escaping from the surface of the neutron star are continuously accelerated to relativistic energies. In the case of the aligned rotator of Goldreich and Julian, the streaming particles comprise several charged beams, confined by the strong magnetic field. Here we need only assume that there is a narrow beam of electrons streaming from the magnetic polar cap—located in the rotational equator[7]—which consequently traces out an expanding helical pattern around the spinning star.

The central part of the Crab has been cleared of thermal gas by this relativistic plasma[8], to a distance determined by pressure balance between the beam and the nebula. For a flux of 10^{38} ergs s^{-1} (consistent with the energy loss due to slowing of the rotation) this radius is $R \approx 5 \times 10^{18}$ cm, roughly the position of the "thin-wisp"[7].

The nebular field is believed to be aligned with the pulsar rotation axis[7], so the beam will encounter a given point once each pulsar period, "injecting" a pulse of electrons moving perpendicular to the field lines. Because the beam is narrow, the differences in the times of injection for various electrons in a given pulse are small compared with the gyration time in the nebular field. All the electrons injected in any given pulse therefore move in phase and, at least initially, radiate coherently.

Differential light-travel-time will destroy the constructive interference of the received radiation—unless there are significant density (and therefore emissivity) fluctuations on the scale of the radiation wavelength. Specifically, the effective coherence factor for a spatial distribution of radiators is proportional to $|a(\boldsymbol{k})|^2$, where $a(\boldsymbol{k})$ is the complex Fourier amplitude of the fluctuations in the beam, evaluated at $k = 2\pi/\lambda_{\mathrm{RAD}}$, in the direction of the observer's line of sight. If the scale of the fluctuations is small compared with λ_{RAD}, complete coherence results.

We must also consider the relative phase drift due to energy differences between the individual electrons. Assume that the synchrotron emission is concentrated around frequency $\nu \approx \gamma^2 \nu_0$, where γ is the relativistic factor and ν_0 is the non-relativistic gyrofrequency,

$$\nu_0 = \frac{eB}{m_0 c}$$

At injection all electrons begin to radiate in phase, but after a time Δt an electron at ν is only coherent with those electrons whose characteristic emission frequencies lie within

$$\Delta\nu \approx \frac{2\pi}{\Delta t} \text{ of } \nu$$

At Δt the spatial density of particles which are in phase at frequency ν is therefore roughly

$$N\left(\boldsymbol{x}, \gamma, \Delta t \frac{\Delta\nu}{2\nu_0\gamma}\right) \approx \left|a\left(\frac{2\pi\nu}{c}\right)\right|^2 \frac{N(\boldsymbol{x}, \gamma, \Delta t)}{2\,(\nu\nu_0)^{1/2}} \; \frac{2\pi}{\Delta t} \; V(\Delta t)$$

where $N \mathrm{d}\gamma \mathrm{d}^3 x$ is the number of particles in $\mathrm{d}\gamma \mathrm{d}x^3$ about (γ, x) at time Δt in the pulse. The net intensity enhancement factor (defined as $A(\nu, \Delta t) = I^{\mathrm{coh}}(\nu)/I^{\mathrm{inc}}(\nu)$) is therefore

$$A(\nu, \Delta t) \approx \left|a\left(\frac{2\pi\nu}{c}\right)\right|^2 \frac{N(\boldsymbol{x}, \gamma, \Delta t)}{2(\nu\nu_0)^{1/2}} \; \frac{2\pi}{\Delta t} \; V(\Delta t)$$

where V is the emission volume at Δt. Because pulses are being injected every $T_p = 2\pi/\Omega_p$ s, we are actually interested in some average value of $A(\nu, \Delta t) = A(\nu)$, which we take to be roughly the value at $\Delta t = \frac{1}{2} T_p$.

It is difficult to estimate $|a(\boldsymbol{k})|^2$, but unless it is unaccountably small at the wavelengths of interest, $A(\nu)$ can easily be large enough to account for the observed brightness temperature. We note also that if $N(\boldsymbol{x}, \gamma, \Delta t) \sim \gamma^{-1.6}$, as it is in the nebula itself, then the intensity varies as

$$I^{\mathrm{coh}}(\nu) = A(\nu) I^{\mathrm{inc}}(\nu) \sim \left|a\left(\frac{2\pi\nu}{c}\right)\right|^2 \nu^{-1.6}$$

which, if we allow for some frequency dependence in

$$\left|a\left(\frac{2\pi\nu}{c}\right)\right|^2$$

is in reasonable agreement with the value of -2 for the measured slope of the spectrum of the small diameter source[5].

Bertotti, Cavaliere and Pacini (IAU Symp. on X-ray and γ-Ray Astronomy, Rome, 1969) have independently suggested a similar mechanism involving coherent, non-magnetic synchrotron emission for the pulsed radiation.

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