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A Model for the Spatial Distribution of Relativistic Electrons in the Crab Nebula

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Abstract. A model for the spatial distribution of relativistic electrons in the Crab Nebula is proposed. Particles injected in the vicinity of the pulsar propagate in a magnetic field of time-dependent but spatially constant intensity. A good description of the nebular synchrotron emission, from radio to X-ray frequencies, is obtained if particle diffusion with respect to the azimuthal field lines is taken into account.

The global radiation spectrum of the Crab Nebula is well described by the classical homogeneous model (Pacini & Salvati 1973) with the standard magnetic field of 3×10^{-4} G. The homogeneity assumption, however, contrasts with the observed decrease of nebular size with increasing frequency and the steepening of optical spectral index with increasing distance from the pulsar. These two facts can be accounted for by assuming particle injection only in the vicinity of the pulsar and that their distribution across the nebula is determined by some propagation mechanism. Viscous diffusion (Wilson 1972b) or MHD propagation (Kennel & Coroniti 1984) have been proposed, but there still doesn't exist a model which describes both the spatial and spectral properties of the emission through the entire frequency interval covered by images.

In this model, the nebula is regarded as a uniformly expanding sphere continuously supplied with energy by the central pulsar, whose spin-down luminosity is converted into magnetic and particle energy with a constant ratio between the two. The magnetic field is assumed to be azimuthal and its intensity spatially constant but time-dependent due to adiabatic losses and the decreasing pulsar input. Particle injection is assumed to occur within an infinitely thin spherical layer near the central pulsar, from where particles propagate through the nebula with a purely radial bulk velocity determined, to the zeroth order, by ideal MHD. The injected spectrum is taken as two power-laws with index 1.54 for radio and optically emitting particles and 2.4 for the X-ray emitting ones. Spectral evolution is due to expansion and radiation losses.

These assumptions define the particle spatial and spectral distribution at any given time and allow calculation of the nebula synchrotron emissivity, given that the particle velocity distribution is isotropic and the emission monochromatic. Comparison of these 0^{th} order model predictions with observations show that with the standard magnetic field only the radio emission can be reproduced, whereas the nebular size at higher frequencies is largely underestimated.

A much better agreement is found by considering the finite extension of the injection region and the existence, as suggested by polarization studies (Woltjer 1958; Wilson 1972a), of radial distortions of the magnetic field structure. These

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two facts have been taken into account by convolving the 0^{th} order particle distribution with a Gaussian whose width is the sum of a constant, related to the size of the injection region, and a term accounting for the dependence on energy of the distance a particle travels across the azimuthal field lines.

This dependence has been found to be mild and the injection to occur within the region in which the wisps activity is observed. This was done by a multifrequency fit, using radio data at 1.4 GHz (Bietenholz & Kronberg 1991), optical data at 6450 Å (Vèron-Cetty & Woltjer 1993) and public ROSAT data with a mean photon energy of 1 keV. Comparison between the model predictions and the data are shown in Figure 1 for the best fit parameters.

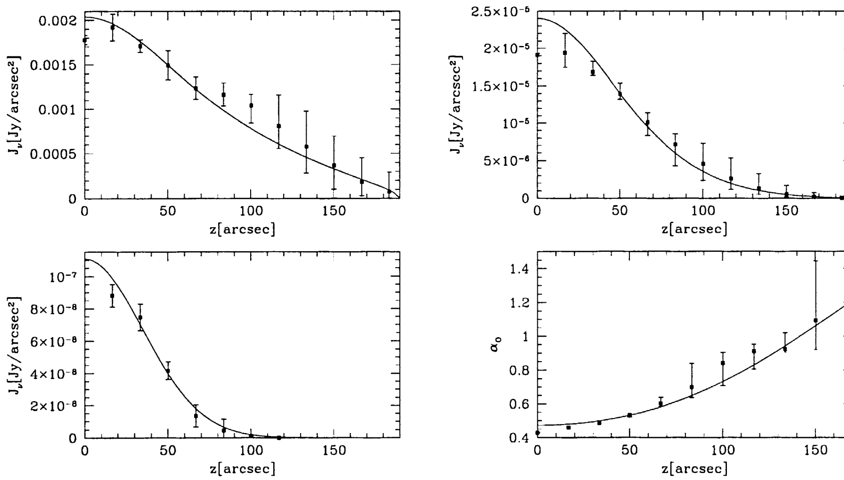

Figure 1. Calculated and observed surface brightness profiles at radio (top-left), optical (top-right), and soft X-ray (bottom-left) frequencies. The optical spectral index (bottom-right) varies across the nebula between 9241 and 5364 Å (Vèron-Cetty & Woltjer 1993). Error bars represent the uncertainty of geometrically averaging intensity profiles along orthogonal directions.

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