Broad-Band Model Spectra of Gamma-Ray Emission from Millisecond Pulsars

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ABSTRACT

We present spectra of pulsed gamma-ray emission expected from millisecond pulsars within the framework of polar-cap models. The spectra are a superposition of three components due to curvature (CR), synchrotron (SR), and Compton upscattering (ICS) processes. The CR component dominates below 100 GeV and the ICS component exhibits a peak at $\sim$ 1 TeV. The CR component should be observable from J0437-4715 with the next generation gamma-ray telescopes, like e.g. GLAST.

KEYWORDS: pulsars, gamma-rays, J0437-4715

1. INTRODUCTION

According to model predictions (Sturner & Dermer 1994, Rudak & Dyks 1998a) the sensitivity of present-day satellite gamma-ray experiments like EGRET is about one order of magnitude too low for millisecond pulsars with high spin-down fluxes to be detected; for upper limits from EGRET see Nel et al. (1996). However, objects like J0437-4715 should be accessible with future missions like GLAST, thus providing a testing ground for magnetospheric models relevant for millisecond pulsars. The aim of this paper is to present major spectral features of pulsed gamma-ray emission (for $E \gtrsim$ 1 MeV) expected when cascades of secondary particles, triggered by ultrarelativistic primary electrons, develop above polar caps of millisecond pulsars with dipolar magnetic fields around $10^9$ G.

3. ACCELERATION OF PRIMARY ELECTRONS

We investigated four different models of electron acceleration. Electrons are instantly accelerated to ultrarelativistic energy in model A, i.e. they are injected with $E_{\text{init}} = E_{\text{max}}$. The values of $E_{\text{init}}$ were chosen (see Rudak & Dyks 1998b for details) to be just above the threshold value for creation of Sturrock pairs: for a standard millisecond pulsar ($B_{pc} = 10^9$ G, $P = 3$ ms) $E_{\text{init}} = 1.07 \times 10^7$ MeV. For J0437-4715, $B_{pc} = 7.4 \times 10^8$ G, $P = 5.75$ ms, and $E_{\text{init}} = 1.54 \times 10^7$ MeV, where we used the magnetic field derived from kinematically corrected $\dot{P}$ by Camillo et al.
The CR energy spectral component due to a single primary electron injected at the outer rim of a polar cap of the standard millisecond pulsar. We normalise the spectrum with $E_{\text{max}}$ - maximum energy of the electron, mediated between acceleration and cooling rates (models B, C, and D). For model A (instant acceleration at the cap surface), $E_{\text{max}}$ is equal to the initial energy $E_0 = 10^7$ MeV. Pulsar parameters are $B_{pc} = 10^9$ G, and $P = 3$ ms.

For comparison, three other models (B, C, and D) for particle acceleration were considered, with different dependencies of the longitudinal electric field on the height $h$:

\[
E(h) = \frac{V_0}{r_{pc}} \times \begin{cases} 
\exp\left[-\frac{h}{r_{pc}}\right], & \text{model B} \\
\exp\left[-\left(\frac{h}{r_{pc}}\right)^2\right], & \text{model C} \\
\max\left\{1 - \left(\frac{h}{r_{pc}}\right)^2, 0\right\}, & \text{model D}
\end{cases}
\]  

(1)

The characteristic scale height of the electric field is equal to the polar cap radius $r_{pc}$ in each case. For each pulsar, the value of the potential drop $V_0$ was chosen to yield a similar number of pairs as in the model A.

3. PRINCIPAL SPECTRAL COMPONENTS

**Curvature Radiation.** CR is the dominant spectral component in the energy
FIGURE 2. Model energy spectrum of J0437-4715 per primary electron. We use model A with $E_{\text{init}} = 1.54 \times 10^7$ MeV, and soft photons coming from the surface with the temperature $4 \times 10^5$ K (Edelstein et al. 1995). The labels CR and ICS denote the curvature and inverse Compton components respectively. Each component includes transfer effects due to magnetic absorption and subsequent synchrotron radiation of the pairs.

range from 1 MeV out to a cutoff at $\gtrsim 0.1$ TeV. Its characteristic features are shown in Figure 1 for the different acceleration models. Due to smaller curvature radii implying higher values of the characteristic photon energy, and also to much weaker magnetic absorption ($\gamma B \rightarrow e^\pm$), the high-energy cutoff is far beyond the cutoffs expected for classical, high-$B$ pulsars (Dyks & Rudak 1998). The slope $\alpha$ of radiation energy per logarithmic energy bandwidth ($E^2 dN/dE \propto E^{-\alpha}$) below 100 MeV is insensitive to the model of acceleration, and is close to 4/3. Above the break at $\sim 100$ MeV the spectrum levels off to a degree which depends on the acceleration model. For models A and B the slope between 100 MeV and 10 GeV is $1/3$ and 0.84, respectively. For models C and D the spectra are practically indistinguishable, with slopes approximately equal to 0.7 between 100 MeV and 1 GeV and then steepening to about 0.87 between 1 GeV and 10 GeV.

**Non-magnetic Inverse Compton.** For millisecond pulsars, magnetic fields at the surface are much weaker than the critical field $B_{\text{crit}} = 4.414 \times 10^{13}$ G. Thus the scattering process of electrons in a field of ambient photons is well described by the Klein-Nishina relativistic non-magnetic cross section. Our treatment of the
scattering process follows Daugherty & Harding (1989). In the non-magnetic case the optical depth for scattering of an electron is small. Thus scattering is not a relevant electron deceleration process. Most of the scatterings take place when the electron is at the height of the order of the size of soft-photons source. We consider two cases of the geometry of the soft photon source. In the first one the soft photons originate on a hot polar cap with temperature $\gtrsim 10^6$ K. In this case most of the ICS photons will pair produce and will not be able to escape. In the second scenario the soft photons come from the entire surface of the neutron star, with the temperature around a few times $10^5$ K. Here most of the scattering events take place at the distance of a few neutron star radii from the surface, thus most photons will escape freely.

4. DISCUSSION

We have calculated broad-band spectra of non-thermal origin for millisecond pulsars within the framework of polar-cap models with magnetospheric activity induced by curvature radiation of beam particles. This non-thermal emission is a superposition of curvature, inverse Compton and synchrotron radiation. The curvature component dominates the region between 1 MeV and 100 GeV. The slope of the spectrum in the range between 100 MeV and 10 GeV is sensitive to the details of the electron acceleration process. The synchrotron component becomes important only below $\sim 1$ MeV. The ICS component has a narrow peak around 1 TeV. In the case of the nearby millisecond pulsar J0437-4715 the curvature component should be detectable with the next generation gamma-ray telescopes (e.g. GLAST). The ICS component is about two orders of magnitude too weak for present day ground based Cherenkov detectors (Bulik & Rudak 1998). The expected broad band gamma-ray spectrum of this pulsar is shown in Figure 2.

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