A multicomponent model for the optical to \( \gamma \)-ray emission from the Crab Pulsar

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Abstract

We present a multicomponent model to explain the features of the pulsed emission and spectrum of the Crab Pulsar, on the basis of X and \( \gamma \)-ray observations performed with BeppoSAX, INTEGRAL and CGRO. This model explains the evolution of the pulse shape and of the phase-resolved spectra, ranging from the optical/UV to the GeV energy band, on the assumption that the observed emission is due to more components. The first component, \( C_2 \), is assumed to have the pulsed double-peaked profile observed at the optical frequencies, while the second component, \( C_3 \), is dominant in the interpeak and second peak phase regions. The spectra of these components are modelled with log-parabolic laws. Moreover, to explain the properties of the pulsed emission in the MeV/GeV band, we introduce two more components, \( C_4 \) and \( C_5 \), with phase distributions similar to those of \( C_3 \) and \( C_4 \) and log-parabolic spectra with the same curvature but different peak energies. This multicomponent model is able to reproduce both the broadband phase-resolved spectral behaviour and the changes of the pulse shape with energy. We also propose some possible physical interpretations in which \( C_4 \) and \( C_5 \) are emitted by secondary pairs via synchrotron mechanism while \( C_2 \) and \( C_3 \) can originate either from Compton scattered or primary curvature photons.

Introduction

The Crab Pulsar (PSR B0531+21) is perhaps the best known rotation-powered pulsar. It has a 33 ms period, and pulsed emission is detected throughout the whole electromagnetic spectrum, from the radio band to high energy gamma rays. The pulse has a characteristic double peak structure with a phase separation of 0.4. It is well known that the pulse shape of the Crab changes with energy in the X and soft gamma-ray ranges where the emission of the second peak (P2) becomes higher than the first one (P1), and where it presents a significant emission from the region between the two peaks (bridge or IP). This behaviour continues up to about 10 MeV, where the pulse almost sharply returns to a shape similar to the optical light curve. A satisfactory explanation for these changes has not been found so far.

On the basis of high quality BeppoSAX data, covering the wide energy range from 0.1 to 9 GeV, we already proposed a two component model (Massaro et al., 2000) to explain this behaviour. Here we extend this model, building upon a reanalysis of the whole set of BeppoSAX Crab observations. We find that the energy spectra of these components are not described by a simple power law, but show a spectral steepening towards high energies. We model these components with log-parabolic spectral distributions. The observations of BeppoSAX are thus well fitted. Moreover, to explain the behaviour in the MeV/GeV band, two more components are introduced, both with a similar shape and spectrum of the X-ray counterparts.

The two-component model: optical to hard X-rays

The first component, called \( C_2 \), is assumed to have the same pulsed profile observed at optical frequencies, while the second component, \( C_3 \), is described by an analytical model whose shape is determined by comparing \( C_2 + C_3 \) with the observed pulse profiles, and that dominates at the interpeak (IP) and second peak (P2) phase regions (fig. 1). X-ray light curves are thus well reproduced (Massaro et al., 2000).

Using the high-statistics observations of BeppoSAX we performed a phase-resolved spectral analysis and found that the photon indices of P1, P2 and IP are changing with energy, and linearly increasing with LogE (fig. 2).

CGRO COMPTEL and EGRET observations (Knippe et al., 2001, Thompson, 2003) provide above \( \sim 10 \) MeV light curves of a good statistical quality which show that the pulse shape turns to be similar to that of \( C_2 \), although some minor differences are present. At energies higher than \( \sim 200 \) MeV the emission from IP and P2 increases, and this seems to reproduce the behaviour of the X-ray emission. In order to explain such a finding, we assume there are two more, high-energy spectral components, \( C_4 \) and \( C_5 \), both with log-parabolic spectral distributions and with the same pulse shape of the lower-energy components \( C_2 \) and \( C_3 \). To be consistent with the upper limits at TeV pulsed emission (e.g. Lessard et al., 2000) we added also an exponential cutoff to both \( C_4 \) and \( C_5 \) at the energy \( E_0 = 15 \) GeV. This model therefore has 6 adjustable parameters, i.e. the normalisations, peak energies and curvatures of the \( C_2 \), \( C_3 \), \( C_4 \) and \( C_5 \) components. Assuming that the curvatures are equal to the \( C_2 \) and \( C_3 \) ones (\( \beta = 0.3 \)), we are then able to well reproduce the broadband energy spectrum of the total (averaged) pulse, and of the P1, IP and P2 phase regions (see fig. 3) and the ratios of P2/P1 and IP/P1 fluxes (in the same phase intervals of Knippe et al., 2001, fig. 4). We stress that there is no constraint on \( E_0 \) in fig. 4(left) we plot also the P2/P1 ratio for various values of \( C_4 \), cutoff energy ranging from 9 to 15 GeV.

Extension of the model to the MeV/GeV band: needs for two more components

MeV/GeV observations (Knippe et al., 2001) provide evidence for two more components, \( C_4 \) and \( C_5 \), both with log-parabolic spectral distributions. The observations of BeppoSAX are thus well fitted. Moreover, to explain the behaviour in the MeV/GeV band, two more components are introduced, both with a similar shape and spectrum of the X-ray counterparts.

Physical interpretation

The open question is the physical origin of these components that phenomenologically will explain the observations, in the framework of the high-energy pulsar emission models, either in the polar cap or outer gap models (e.g. Cheng et al., 2000, Zhang & Cheng, 2002). Assuming that the low-energy components \( C_2 \) and \( C_3 \) are produced by synchrotron emission of secondary electron–positron pairs created in the pulsar magnetosphere, the higher-energy components \( C_4 \) and \( C_5 \) could be due to:

- Emission of curvature radiation from primary particles accelerated in the electrostatic gap.
- Emission from inverse Compton scattering of the synchrotron photons by the secondary pairs themselves (Synchrotron-SSC Compton mechanism). The different shape of the "O" and "X" components is presumably due to the different location in the magnetosphere of the emission region.

Conclusions

This model is able to give a consistent interpretation of the various peculiarities inherent to the high energy emission from the Crab Pulsar. Clearly, it is only a phenomenological model, but it could furnish some constraints to more detailed, physically-based emission models. In particular it is important to verify whether at energies higher than \( \sim 1 \) GeV the pulse shape tends to be dominated by \( C_3 \). The GLAST/LAT experiment (Gruber et al., 1999), with its large collecting area, will give us very useful data in this range that will permit to better estimate the model parameters. Another interesting perspective is the adaptation of the model to other pulsars.

References


Figure 1: The two components \( C_2 \) and \( C_3 \) of the model at the energies of 0.1 keV (left) and 7.5 keV (right). In the upper panel, the model compared with BeppoSAX data. In the lower panel \( C_2 \) and \( C_3 \) from Massaro et al. (2000).

Figure 2: Photon indices of P1, IP and P2 as measured by the four SFI of BeppoSAX and by INTEGRAL-IGRIS.

Figure 3: Broadband spectra of the total averaged pulse and of P1 with the four components of the model.

Figure 4: P2/P1 (left) and IP/P1 (right) ratios as derived from the model. Data points come from various experiments (Knippe et al. 2001).