Search for VHE pulsed emission from the Crab pulsar with the CELESTE experiment

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Abstract

The CELESTE experiment, operating at the THEMIS site, in the French Pyrénées, started collecting data on the Crab pulsar with a 40 heliostat array in February 1999.
The $\leq$50 GeV trigger threshold of CELESTE allows us to search for the pulsed emission of the Crab pulsar in an unexplored energy window. These observations are expected to provide important constraints on the models of pulsar electrodynamics. After discussing motivations for such observations in the framework of existing observations in adjacent energy ranges, we present specific timing analysis.

1 Introduction

Radiation from the Crab consists of both pulsed and unpulsed components over a broad energy range from radio to gamma rays. The unpulsed component is attributed to the synchrotron radiation from the relativistic wind of electrons from the pulsar in the magnetic field of the nebula (DeJager & Harding 1992, Atoyan & Aharonian 1996). Inverse Compton scattering (IC) of infrared to optical photons of the nebula by this relativistic wind is primarily responsible for emission above $\sim$ 1 GeV.
Radiation mechanisms for pulsed emission from the pulsar, probably of magnetospheric origin, are less well understood. Models suggest that primary charged particles, accelerated in vacuum gaps in the corotating magnetosphere, initiate electron-positron cascades by interaction of their curvature radiation with the strong magnetic field. In polar cap models (Daugherty & Harding 1996 and references therein), the accelerator gap lies near the magnetic poles, where the accelerated primary charged particles emit curvature/synchrotron radiation. In the outer gap model (Cheng, Ho & Ruderman 1986, Romani 1996 and references therein), the accelerator gap forms in the outer magnetosphere. Synchrotron radiation of the lower energy charged particles is responsible for emission below 1 GeV, while radiation at higher energies is produced by IC scattering of the electron-positron pairs off the low energy photons.
Two main parameters constrain a possible pulsed emission. First, the strength of the accelerator field sets an upper limit on the maximum energy of the primary charged particles. Then, the escape capability of high-energy photons depends crucially on the magnetic field intensity and orientation. With these limitations, both polar cap and outer gap models predict a spectral break or cutoff above a few GeV. However, an additional pulsed component at higher energies cannot be ruled out, as pointed out by Romani (1996). In a revised version of the outer gap model, this author predicts a pulsed component at TeV energies, due to IC of the synchrotron photons of the pulsar within the magnetosphere.
Thus, observations in an intermediate energy range between GeV and TeV are strongly required, as information on the position of an expected spectral break/cutoff and on the spectral shape in this energy region would constrain the radiation parameters described above. Exploring the energy region between 30 GeV and 300 GeV is precisely the goal of the CELESTE atmospheric wavefront sampling experiment.

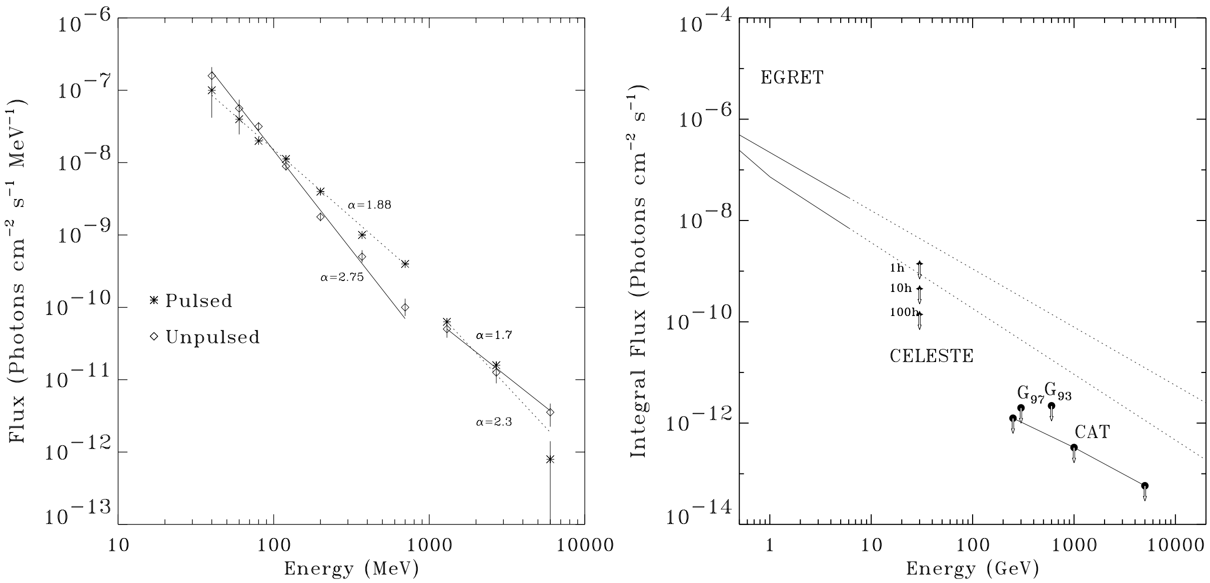

Figure 1: *Left:* Differential unpulsed (diamonds) and pulsed (asterisks) fluxes from the Crab pulsar as a function of energy in the EGRET energy range (Ramanamurthy et al., 1995). *Right:* Integral pulsed flux as a function of energy. Solid lines are for the EGRET integral flux (upper part: Nolan et al. 1993, lower part: Ramanamurthy et al. 1995). The dashed lines represent the extrapolations of these integrated fluxes. At TeV energies, we report the upper limit set with the CAT telescope (OG.2.2.05, this conference). Other upper limits are from Goret et al. 1993 (G93) and Gillanders et al. 1997 (G97). We show expected limits for a 5σ detection of the pulsed emission of the Crab pulsar with CELESTE in 1, 10 and 100 hours of data, assuming an optimal trigger threshold of 30 GeV.

2 Previous high energy observations of the Crab Pulsar

The spectral properties of the pulse profile of the Crab pulsar have been investigated by both COS B (Clear et al. 1987) and the EGRET telescope on the Compton-GRO satellite. EGRET has shown that the pulsed component of the Crab is a power law extending up to a few GeV. Nolan et al. (1993) characterize the observed emission between 50 MeV and 10 GeV with a power law spectrum of photon index 2.15. As the pulsed fraction seems to decrease with increasing energy above 1 GeV, Ramanamurthy et al. (1995) study the spectrum in different energy bands, leading to a more realistic power law slope of 2.3 above 1 GeV.

Nevertheless, a spectral break (or cutoff) can not be firmly confirmed due to the weak sensitivity of the experiment at these energies. Since the eighties, Cherenkov Imaging devices on the ground permit high gamma ray observations. Although some groups report evidence for a transient TeV pulsed emission (Gibson et al. 1982, Bhat et al. 1986, Acharya et al. 1992), long term observations show no modulations, but are still under study (OG.2.2.05, this conference, Goret et al. 1993, Gillanders et al. 1997).

Both satellites and ground-based telescopes did detect the steady emission from the pulsar and nebula. The intermediate energy range between satellites and Cherenkov atmospheric imaging telescopes, falling right in CELESTE's window $30 \leq E \leq 300$ GeV, remains unexplored.

3 The CELESTE experiment-Some Predictions

CELESTE is an atmospheric Cherenkov wavefront sampling experiment at the THEMIS site, in the French Pyrénées, using the "recycled" Electricité de France (EDF) solar power plant array.

A description of the detector configuration and trigger scheme is given in OG.4.3.06 (this conference). After a preliminary period with a 18-heliostat array, CELESTE is now running with 40 heliostats and 20 Flash ADC's.

The increased sensitivity leads to a lower energy threshold below 50 GeV. We have used MonteCarlo simulations to estimate what CELESTE's performances should be. Confirmation of the MonteCarlo predictions will be possible only after we have a clear signal from the continuous emission of the Crab. Even so, we can do the exercise of seeing what sensitivity CELESTE might attain. We will use a collection area of 1.5×10^4 m^2 and a γ-ray efficiency of 0.8 at the trigger level. Any offline cuts to reduce hadrons will reduce this efficiency. In order to derive the expected number of pulsed photons detected by CELESTE, we extrapolate and integrate between 50 and 300 GeV the high-energy pulsed spectrum of the Crab pulsar observed by EGRET, with the above instrumental constraints. By analogy with the light curves as observed with the EGRET telescope (2 main peaks 0.1 wide in phase), we assume a duty cycle of 20%.

Using data from Nolan et al. 1993 (see above) for the EGRET spectrum, we expect $\sim$18 photons per minute in the CELESTE energy range. Assuming a trigger rate of $\sim$20 Hz (as observed in the current period), the pulsed component from the Crab should then be detectable by CELESTE at the 5σ confidence level in about 15 minutes. Obviously, this is an unrealistic view as the pulsed component seems to decrease more sharply towards high energies. We thus assume a spectral break at 1 GeV as described in Ramanamurthy et al. 1995. In such conditions, we need 8 hours of data to detect the pulsed component of the Crab pulsar at the 5σ confidence level. With an optimal trigger threshold of 30 GeV, as expected in the stabilized 40-heliostat configuration, this value would lower to 2.2 hours of data.

Non detection of the signal at this level would put stringent constraints on the shape of the pulsed spectrum in this energy range. In this case, we need to concentrate analysis on hadron rejection, and study the level of contamination of pulsed photons by photons from the pulsar steady emission.

4 Data analysis

Before the Crab pulsar disappeared for the season, CELESTE started observing this source with the new 40-heliostat configuration. Among technical and weather constraints, 3 hours of data were collected, with an average of 24 heliostats.

4.1 Event selection

We see in fig.2 Flash ADCs data corresponding to 6 of the 40 heliostats for a typical Cherenkov event. For each event, we first search for peaks in the Flash ADC data, and thereby estimate the Cherenkov amplitude and arrival time for each heliostat. The distribution of arrival times then permits reconstruction of the spherical wavefront of radius (11km)/cos(θ) where θ is the zenith angle. In order to reduce effects of the night sky background, cuts are imposed on the overall peak amplitudes on the heliostats. Cuts on the χ^2 distribution of the wavefront timing fit and the position of the reconstructed sphere's center are intended to reject hadron showers while preserving the gamma signal. A more detailed description of the methods and cuts is given in OG.2.1.20.

4.2 Timing analysis

All arrival times of the triggered events are flagged with a GPS instrument. In order to validate our time measurements, we compared the arrival times of the cherenkov events seen by CELESTE with those detected by the CAT 17 m^2 imaging telescope, located in the heliostat field. Indeed, number of common events, mainly hadrons, with the 200 GeV-10 TeV imager, are expected. With a 1.2 hour dataset, we found 20% ($\sim$ 11000 events) of the CELESTE events and 16% of the CAT events matching within 2μs. The number of accidental coincidences is estimated to be less than 10 events. This 2μs accuracy is adequate for a phase-resolved study of the 33ms Crab pulsar.

Since November 1998, we added a barycentric correction tool to CELESTE's data acquisition. Arrival times are transformed to Solar Barycentric Time T. For each event, the corresponding rotational phase is the fractional part of the number of periods since a reference epoch T_0, given by the following Taylor expansion:

$$\phi(T) = \phi(T_0) + f_0(T - T_0) + \frac{1}{2}f_1(T - T_0)^2 + \frac{1}{6}f_2(T - T_0)^3, \tag{1}$$

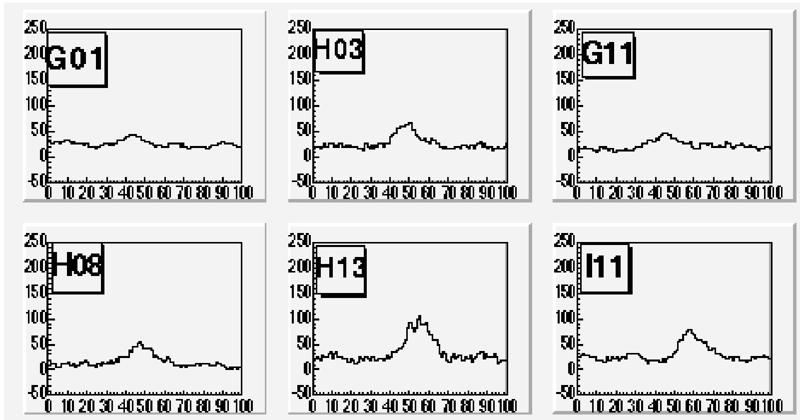

Figure 2: Typical view of a Cherenkov event in several 930 MHz Flash ADC's. Analog and logic delays compensate for the path length differences between the heliostats, so that the signal is centered in each Flash ADC's window. Each window is 100-bin wide, with a bin size equal to inverse Flash ADC's frequency. Signal amplitude is in digital counts (with 2 dc's corresponding to 1 photoelectron)

where f_0,f_1 and f_2 are the pulsar spin frequency and first derivatives measured at the reference epoch T_0. Ephemeris were taken from the Pulsar Timing Database at Jodrell Bank (Lyne & Pritchard, 1999). With the above calculations, we search for modulations at the Crab pulsar frequency by folding all arrival times in a 50 bin phasogram.

5 Conclusions

At the present time, a preliminary data analysis revealed no evidence for a pulsed component over CELESTE's trigger threshold ($\leq$50 GeV) in the 3 hours of data collected on the Crab pulsar. This favours the hypothesis of a sharp break or exponential decay in the spectrum near $\sim$ 50 GeV, with all cautioussness imposed by our restricted dataset. But analysis is still under way. More results will be presented at the conference.

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