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Search for high energy gamma ray pulsar emission with the CELESTE Experiment

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Abstract. The CELESTE experiment detects gamma rays in the 50 GeV range by measuring the atmospheric Čerenkov light collected using 40 of the heliostats of the Thémis central tower solar facility. We have recently announced an upper limit for the exponential energy cut-off in the spectrum of the Crab pulsar $\frac{dN}{dE} = KE^{-\gamma}e^{-\frac{E}{E_0}}$ with $E_0 = 32GeV$. This result was obtained with the CELESTE standard analysis used for the study of the continuous emission from the nebula. We discuss here an analysis of CELESTE data which preserves low energy events in order to study the pulsed component. We also present very preliminary results for PSR1951+32 which may be the most promising candidate for the first detection of a gamma ray pulsar by a ground based experiment.

1 Introduction

Since the beginning of winter 1999, CELESTE has reached its cruising speed with a setup of forty heliostats giving stable conditions for data analysis. The results on the Crab Nebula and the measurement of its flux at 60 GeV is detailed in de Naurois (2001). The results on the blazars Mrk421 and Mrk501 are reported elsewhere in these proceedings (Le Gallou , 2001). We discuss some new results on gamma pulsars following those presented this winter (Durand , 2001).

CELESTE is a Sampling and Timing Cerenkov Experiment located at Thémis a former tower solar power plant in the eastern French Pyrénées (N. 42.50, E. 1.97, alt. 1650m). CELESTE uses forty $54\mathrm{m}^2$ heliostats to collect the Čerenkov light from air showers. The experimental setup is summarized in these proceedings (Le Gallou , 2001) and detailed in CELESTE experiment proposal (1996) and Reposeur (2001).

2 Crab Pulsar

2.1 Results on the Nebula

For a steady source Čerenkov experiments use the ON-OFF method, where for each ON source data run, there is an OFF source measurement acquired in the same conditions. Small changes in the night sky background change the trigger rate slightly and thus bias the ON-OFF measurements. We remove this bias by raising the energy threshold via a pulse-height cut in the offline analysis.

After this pre-analysis two cuts are applied, the first one is an amplitude cut to allow a good Čerenkov wavefront reconstruction, while the second one tests the homogeneity of the Čerenkov light distribution. The energy threshold after these cuts increases to 60 GeV. The differential flux for an assumed $1/E^2$ spectrum we found is $(3.3 \pm 0.5 \pm 1.1) \times 10^{-8}/E^2$ photons/cm^2/s/GeV.

2.2 Crab Pulsar

The study of the pulsed component requires being able to accumulate data from runs taken over a very long period. CELESTE event dating in the local frame is given by a GPS Clock tagged by the triggering system. This local time is converted in the solar system barycentre frame using the JPL DEC-200 ephemeris (1997). Pulsar radio ephemeris are used to build the phase histogram. For the Crab we used values from Jodrell Bank. The ephemeris for PSR B1951+32 was provided by the Nançay Radio telescope (Cognard , 2001).

2.2.1 Optical data

In order to validate the complete (hardware+software) timing procedure, we have observed the Crab pulsar in the optical range. The PMT anode currents of six of the forty heliostats were converted to voltage, AC-coupled and recorded on six channels of a 16-bit ADC PC board at a frequency of 2000Hz. The timing reference is given by a test signal triggering the CELESTE acquisition system with its GPS clock.

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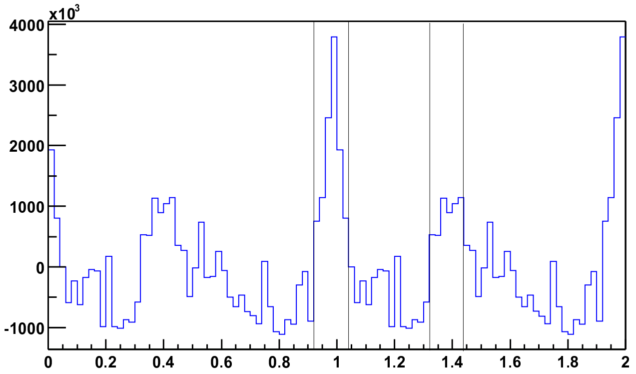

Fig. 1. Crab pulsar optical phase histogram. 100Hz frequency (street lights) is removed by software.

This test signal was also recorded on the last channel of the ADC in order to allow a synchronisation of the currents data with the GPS time.

The phase histogram obtained with this setup is shown in figure 1 exhibiting the two expected peaks in the phase range 0.94-0.04 and 0.32-0.43, in good agreement with radio observations (Fierro , 1998). This result allows us to be confident in our timing procedure.

2.2.2 Results with standard analysis

We first study the pulsed gamma emission using data passing our standard analysis procedure detailed in de Naurois (2001). This pulsar analysis was reported in Durand (2001) and summarized in table 1. The dataset contains only selected good quality runs taken in the same stable triggering conditions (3/5 majority) and 11km altitude pointing (for the lowest energy threshold, see de Naurois (2001)). Thus only 12.1h of the 14.1h dataset are used for the pulsar search.

Uniformity of the obtained ON and OFF phase histogram, tested by the statistical H-Test of De Jager (1994), doesn't exhibit any statistically significant pulsed signal. The method of Helene (1983) was used to obtain an upper limit to the differential flux spectrum of the Crab pulsar emission. We use this method to determine the upper limit on the number of pulsed events in the phase interval corresponding to the radio peaks and found 332 pulsed events at the 99% confidence level corresponding to 12% of the observed steady signal.

First we took the double power law resulting from Egret's measurement (Fierro , 1998) attenuated by an exponential cutoff

$$\left.\frac{dN}{dE}\right|_{att} = \left(0.7\,(E/100)^{-4.89} + 2.3\,(E/100)^{-2.05}\right) e^{-\frac{E}{E_0}} \quad (1)$$

in $10^{-8}\mathrm{photons/cm^2/s/Mev}$. This flux convoluted by our acceptance after cuts gives for the energy cut off $E_0 = 32\mathrm{GeV}$. This value includes the 30% uncertainty on the energy determination. The energy position of the CELESTE point is $55\mathrm{GeV}$, enough to constrain the high energy emission more than other measurement but not enough to conclude on the emission model.

Table 1. Crab pulsar results with standard analysis

Total observation time	12.1h
Total number of OFF events	64295
Total number of ON events	67022
Number of ON events in expected phase windows	14062
Number of ON events outside expected phase windows	52960
Pulse Phase fraction δ	0.21
Significance for the pulse phase domain	-0.12σ
Upper limit at the 99% level using Helene method	$N_p \leq$332

2.2.3 Sensitivity of timing versus ON-OFF analyses

In this section we will try to roughly estimate our sensitivity to the pulsed emission of the Crab. Since the gamma ray signature is no longer the ON-OFF difference, which is very sensitive to drifting measurement conditions, but the phaseogram peaks, we no longer need to apply the software trigger to remove the events near threshold. Furthermore, since we no longer subtract the OFF source data the fluctuations in the OFF data no longer decrease the sensitivity.

Consider as an example our sensitivity to the Crab. The observed ON-OFF rate is $S = 3.8\gamma/min$ (de Naurois , 2001) (table 2), including the 20% acquisition deadtime. The total number of events from the raw trigger is $N_{raw} = 894494$ giving a $20Hz$ rate. After the ON-OFF "standard analysis", the OFF rate, according to table 1, becomes $B_{sa} = 1.5Hz$, and the significativity ($ST/\sqrt{2B_{sa}T}$) gives $2.2\sigma.hour^{-1/2}$. For the pulsar analysis we can replace $ST/\sqrt{2B_{sa}T}$ by $ST/\sqrt{\delta B_{sa}T}$ for a ON "standard analysis" where δ is the phase interval of the expected peak. The gain in significance is thus $Q = \sqrt{2/\delta}$. Thompson (2001) suggests that at the highest energy only the second peak remains for the Crab, for which $\delta = 0.11$, giving $Q = 4.26$.

A consequence of this improved sensitivity is that larger background rates can be tolerated. For the pulsar, where we expect the signal (should there be one) to be just above the trigger threshold having the largest acceptance possible at low energy is the most important criterion.

Figure 2 shows how the energy-dependent effective area evolves with the cuts. As stated earlier, very small changes in atmospheric conditions can change the lowest energy part of the "raw" curve significantly and at this time we have not quantified the resulting uncertainty.

The phase histogram without any cuts is still statistically flat (figure 3). Results from the pulsar analysis using raw data are shown in table 2. The upper limit estimation with the Helene method would give an energy cutoff degraded by our 30% energy scale uncertainty of $E_0 = 23\mathrm{GeV}$. However due to the uncertainties we continue to quote the "standard analysis" value of $E_0 = 32\mathrm{GeV}$ from Durand (2001) and shown in figure 4. Our point is that in order to see a low energy signal the analysis may reject hadrons but mustn't decrease gamma acceptance near threshold.

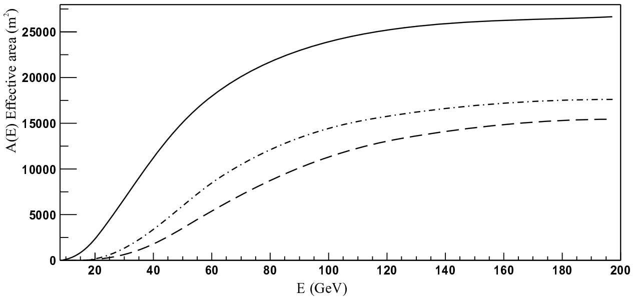

Fig. 2. Celeste acceptance curves for the Crab pulsar at the transit. Solid line gives the acceptance for the raw data, dashed line after the standard analysis cuts, dot-dashed line for an analysis without software trigger.

3 PSR1951+32

Its status of "standard candle" makes the Crab the first candidate for a gamma pulsed signal analysis. However PSR1951+32 which does not exhibit a cutoff in its power spectrum at EGRET energies seems to be a promising candidate for the first detection of a gamma pulsar.

During Summer 2000, CELESTE accumulated 15.8 hours of data on PSR1951+32 with a counting rate around 10Hz (20Hz for the crab during Winter). Analysis conditions differ from those of the Crab observation, no quality selection is applied, the dataset contains runs taken with the two CELESTE pointing strategies 11km and double pointing 11/25 km. The trigger condition is also inhomogenous, mixing runs taken with a 3/5 and 4/5 multiplicity (see Reposeur (2001)). Results using raw data (no cuts are applied) are presented in table 3.

As for the Crab analysis no statistical excess appears in the expected Egret peaks phase range 0.12-0.22 and 0.48-0.74 (Ramanamurthy , 1995). However the unstable triggering conditions do not yet permit a realistic estimation of the energy cutoff imposed by CELESTE.

3.1 Discussion

We can nevertheless try to estimate how CELESTE will be able to constrain pulsed emission. Figure 5 shows the EGRET data for PSR1951+32 and the 75 GeV exponential cutoff deduced from the Whipple's upper limit (Srinivasan et al , 1997). Also shown is a polar cap cut-off prediction of 40 GeV taken from De Jager (2001). To give an general idea of CELESTE's sensitivity, we have placed our *Crab* (not PSR1951) point on the plot. Cheng & Ding (1994) derive spectra and light curves assuming an Outer Gap. They predict a spectral shape of $\frac{dN}{dE} = ke^{-E/E_0}/E^{1.5}$ with $E_0 = 9 \times 10^{-21}\alpha^{-21}P^{-17}B^7 sin\theta$ with $P = 0.04s$ is the pulsar period for PSR1951+32, B is magnetic field strength in 10^{12} Gauss, and where $\alpha = r/r_L$ is the ratio of the radius of the emitting region near the outer gap to the radius of the light cylinder. Using this model, Whipple concludes that $\alpha > 0.6$.

Table 2. Crab pulsar results using raw data

Total observation time	12.1h
Total number of ON events	848853
Number of events in primary pulse expected phase window	85099
Number of events in secondary expected phase window	93686
Number of events in pulses expected phase window	178785
Number of events outside expected phase window	670068
Pulse Phase fraction (two pulses) δ	0.21
Significance for the pulse phase domain	1.4σ
Upper limit at the 99% level using Helene method	$N_p \leq$1787

Table 3. PSR1951+32 pulsar results using raw data

Total observation time	15.8h
Total number of ON events	224657
Number of events in primary pulse expected phase window	22193
Number of events in secondary expected phase window	58835
Number of events in pulses expected phase window	81028
Number of events outside expected phase window	143629
Pulse Phase fraction δ	0.36
Significance for the pulse phase domain	0.66σ
Upper limit at the 99% level using Helene method	$N_p \leq$1102

We can try to predict the rate in γ/minute for PSR1951+32 with different hypotheses. Table 4 suggests that the expected rates are comparable to the Crab Nebula flux. So as shown in figure 5, after one or two seasons of good quality data, CELESTE has a good chance of detecting a signal from PSR1951+32.

4 Conclusion

CELESTE is now able to take data in stable conditions for pulsar observations. The well understood standard analysis used for the ON-OFF study of steady sources leads to an increase of CELESTE's threshold unfavorable to pulsed component detection. So a specific analysis without low energy cuts is being developed. Our understanding of CELESTE ac-

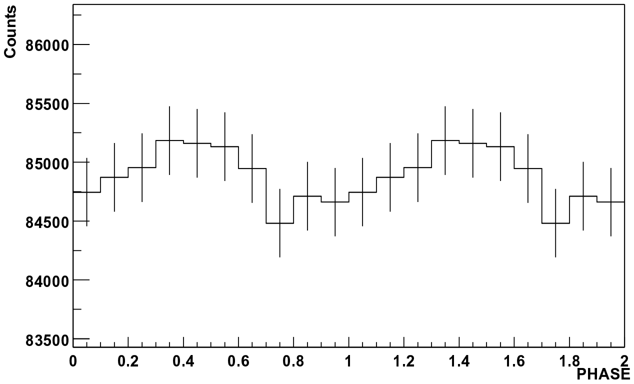

Fig. 3. Crab phase histogram for raw dataset. The histogram is statistically flat

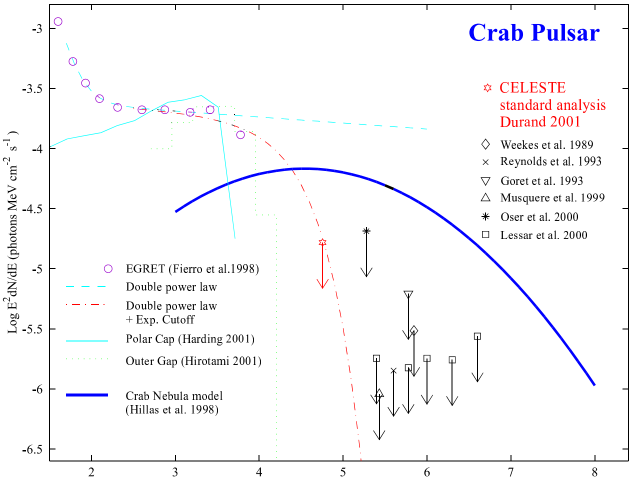

Fig. 4. Crab pulsar spectrum. Solid curve is the Polar Cap (Harding (2001) private communication), the dotted histogram corresponds to the Outer Gap model (Hirotani , 2001). The dashed line is the double power-law fit of EGRET data, the dot-dashed line is the same cut with the exponential cutoff at the energy $E_0 = 32$GeV obtained with the CELESTE standard analysis.The upper limits are those given by different ACT. Note the STACEE upper limit (Oser , 2001) at 190GeV using also a converted solar farm. The thick line is the Hillas (1998) model for the unpulsed GeV-TeV emission from the Crab Nebula.

ceptance for low energy events is poor at present leading to large uncertainties for flux measurements and upper limits. However as we improve our understanding of the detector CELESTE should be able to constrain emission models and draw conclusions on high energy processes in pulsars.

PSR1951+32 with its uncut power spectrum at high energy seems to be the most promising candidate for a pulsed emission detection. Observations made last year do not allow us to constrain its energy cutoff. Analysis is in progress of data taken this year, increasing our statistics. Results on this analysis will be presented at the conference.

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Table 4. PSR1951+32 predicted rate in γ/minute. The cutoff is “polar cap” from De Jager (2001) ($\left(e^{-E/E_0}\right)^2$) with $E_0 = 40GeV$. “Degraded” means that the energy is shifted by our 30% uncertainties. Note that this table is calculated for our raw acceptance.

Function	Nominal	Degraded
EGRET power law	14.4	10.9
EGRET power law + cutoff	1.6	0.6
$E_0 = 1530GeV(\alpha = 0.6)$	16.2	12.0
$E_0 = 60GeV(\alpha = 0.7)$	4.8	2.6

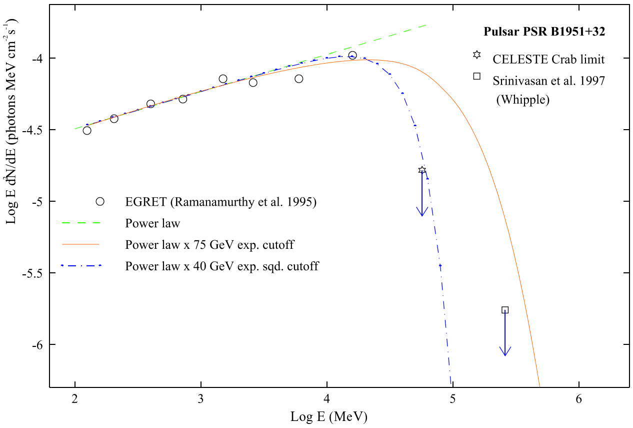

Fig. 5. CELESTE awaited upper limit or detection for PSR1951+32. The dashed line is the power law fit of Egret data, the solid line is the power law multiplied by the 75GeV exponential cutoff (Outer Gap), the dot-dashed line represents the power law cut by $\left(e^{-\frac{E}{E_0}}\right)^2$ (polar cap) taken from (De Jager , 2001)

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