Proceedings of ICRC 2001: 2609 © Copernicus Gesellschaft 2001

ICRC 2001

60 GeV flux from Mrk421 using the CELESTE experiment

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Abstract. The CELESTE experiment detects gamma rays in the 50 GeV range by measuring the atmospheric Cherenkov light collected using 40 of the heliostats of the Themis central tower solar facility. This talk will present observational results on the blazars Mrk421 and Mrk501. Flares have been observed on Mrk421 in Winter 2000 and 2001, and a mean flux has been measured on this source. Mrk501 observations are also reported here. There is some indication for a signal on this source.

1 Introduction

CELESTE has been running on a stable basis since October 1999, with a 40 heliostat array. Our detection of the Crab Nebula and the measurement of its flux at 60 GeV are detailed in de Naurois (2001). This report presents our results on the blazars Mrk421 and Mrk501. These sources are the X-ray selected BL Lac objects which show the strongest flares at TeV energies. Their high energy emission is correlated in different ranges of the electromagnetic spectrum and show intraday variability (Piron (2001); Maraschi (1999); Petry (2000)).

The CELESTE experiment uses 40 of the 54 m^2 heliostats of the former solar plant Thémis in the French Pyrénées (N. 42.50, E. 1.97, altitude 1650 m) to collect air shower Čerenkov light. The collected light is focused on one PMT per heliostat via secondary optics located at the top of a 100 m tall tower. The experimental setup is detailed in Dumora (1996) and Reposeur (2001). The STACEE experiment, located in the USA, is running on the same basis (Oser, 2001). The CAT imager is also located on the Themis site (Piron, 2001), and the Asgat (Goret, 1993) and Themistocle experiments (Baillon, 1993) were ran there until last year.

The trigger is based on the analog sums of the PMTs in 5 groups of 8. Three of these groups are required to reach 4.5 photo-electrons (PE) per heliostat. The PMT signal is continuously sampled by 1 GHz, 8 bit FADCs with a 2 μs buffer. 100 ns of this buffer, located around the nominal position of the signal, is read out for each triggering event.

Results on the pulsed component of the Crab pulsar are presented elsewhere in these proceedings (Dumora, 2001). Previous results on Mrk421 were presented in Holder (2001).

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2 Data Sample

Different heliostat pointing strategies have been studied with CELESTE. The strategies used during the observations presented here are convergent viewing, mainly at 11 km but with some data at 17 km altitude, and the double pointing method where half of the heliostats point at 11 km and the other half at 25 km altitude. In convergent viewing, the heliostats point at the shower rather than at the source itself.

A selection using quality criteria has been applied to the data before including it in the analysis dataset. These criteria are based on the stability of the PMT anode currents and on the trigger group counting rates.

The analysis dataset is summarized in the following table.

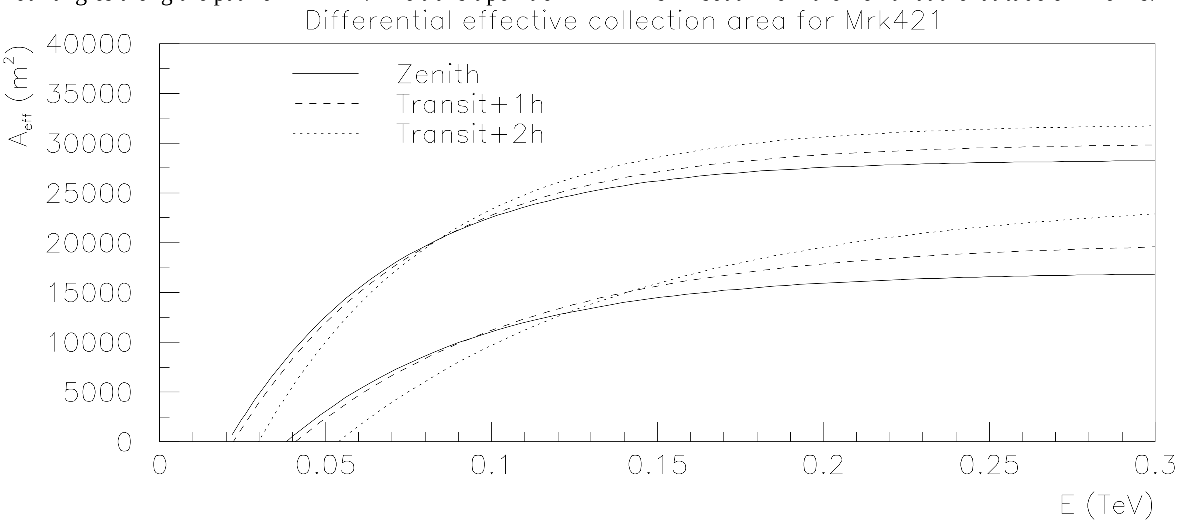
Source	Observation period	Runs	Obs. time (h)
Mrk421	12/1999 - 02/2001	107	31.5
Mrk501	03/2000 - 07/2000	50	14.4

Source	11 km runs	17 km runs	11/25 km runs
Mrk421	67	8	32
Mrk501	15	3	32

3 Analysis

The Čerenkov signal having the same order of magnitude as the night sky background (NSB) collected by the heliostats, CELESTE is very sensitive to systematic effects due to differences of this background between the ON source observation and the OFF source control data. This sensitivity is

Fig. 1. Differential effective collection area at the trigger level (upper curves) and after analysis cuts (lower curves), for the Zenith and two hour angles along the path of Mrk421. The transit point of Mrk421 is 4^0 south from the Zenith at the latitude of Thémis.



particularly evident in the case of Mrk421, a 6.1 magnitude star being located in the same field of view as this active galactic nucleus (AGN). The mean PMT anode currents are in this case 15% higher in the ON than in the OFF source data. The compensation of these differences is performed using an adaptation of the software padding method proposed by Cawley (1993) for use with our FADC data (de Naurois, 2001), followed by a software trigger requiring ≥ 4 groups with > 5 PE per heliostat. We also require ≥ 10 Čerenkov peaks with an amplitude > 25 digital counts in our FADC ($\simeq$ 9 PE) to ensure the quality of the shower reconstruction at the hadronic rejection step of the analysis. Both operations increase the energy threshold but correct efficiently the NSB bias.

Hadronic rejection is performed using two parameters. The first, τ_{50}, reflects the intrinsic time width of the Čerenkov wavefront. It is defined as the FWHM of a peak which is built by summing all channels' FADC signal sample by sample after having adjusted the time origin of the sum to the spherical wavefront fitted using the signal arrival time on each heliostat.

The second, θ, is the reconstructed shower axis angle relative to the pointing direction, described in de Naurois (2001). The behaviour of both parameters in real data is well reproduced by the Monte Carlo simulation for γ-rays. The sensitivity of τ_{50} to the difference of NSB between ON and OFF source data has been demonstrated to be negligeable. The cuts $\tau_{50} < 8.5\ ns$ and $\theta^2 < 50\ mrad^2$ keep 40% of the γ while rejecting 90% of the background.

The results presented here have been obtained using an analysis which is independent of the one presented in de Naurois (2001). The most significant difference between these two analyses is that the former does not use the light pool homogeneity information, while de Naurois (2001) does. Results given by the two analyses on the Crab Nebula match. Comparison of their results on Mrk421 and Mrk501 data is in progress.

4 Effective collection area

Effective collection area and cut efficiencies for γ rays have been calculated using Monte Carlo simulation of the showers and of the detector. Shower simulation has been performed using the CORSIKA package (Capdevielle, 1992). The effective collection area has been studied for various pointing angles and fitted by the function :

$$A(E) = A_0(1 - e^{-\frac{E-E_0}{E_C}}) \quad (1)$$

This function is plotted in figure 1 for 3 pointing angles along the path of Mrk421. As the source drifts away from transit both the energy threshold and the effective collection area at high energy increase. This behaviour is due to first order to the projection geometry of the Čerenkov lightpool on the ground.

At the transit of Mrk421, when using the 11 km convergent pointing strategy, the parameters of $A(E)$ are $A_0 = 2.8.10^4\ m^2$, $E_0 = 20.7\ GeV$ and $E_C = 50.1\ GeV$ at the trigger level and $A_0 = 1.7.10^4\ m^2$, $E_0 = 38.2\ GeV$ and $E_C = 59.2\ GeV$ after analysis cuts. For comparison, the same parameters for the transit of the Crab nebula at the trigger level are $A_0 = 2.8.10^4\ m^2$, $E_0 = 15.3\ GeV$ and $E_C = 32.2\ GeV$. The acceptance has been also calculated for the other pointing strategies.

The total acceptance of the detector is calculated by integrating $A(E)$ weighted by a spectrum assumed to be $\propto E^{-\alpha}$. The value $\alpha = 2$ is consistent with previous observations in the GeV and the TeV range (Buckley, 1999) and with what we can predict from Synchrotron Self Compton (SSC) models (Ghisellini (1996); Qian (1998)). The energy threshold, defined as the maximum of the function $E^{-\alpha}A(E)$, is 36 GeV at the trigger level and 60 GeV after analysis cuts at the transit of Mrk421. Both thresholds increase by 40% two hours away from transit. Varying the assumed spectral index by $\pm\ 0.25$ leads to an uncertainty of $\pm\ 5\%$ in the energy

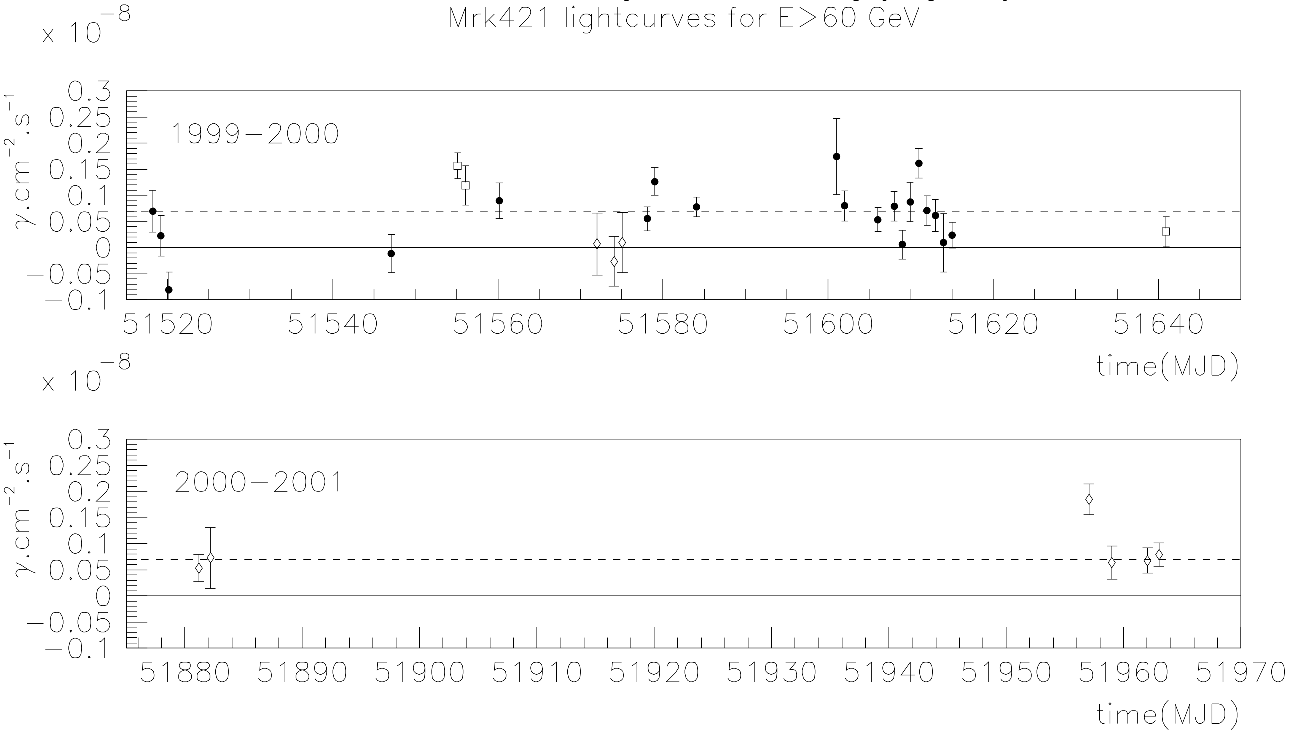


Fig. 2. Nightly averaged integral flux above 60 GeV for Mrk421. Error bars display only statistical errors. The overall systematic uncertainty on this fluxes is 40%. The dashed line is the mean value. Dots, squares and diamonds display respectively 11km, 17km and 11/25km data.

threshold and of $\pm$ 15% in the integrated acceptance.

The overall uncertainty on the acceptance is dominated by the Monte Carlo simulation, the difference between CORSIKA and KASKADE leading to the value of 25%. It is also sensitive to the choice of α, and to cut efficiencies (20%). The variation of the total acceptance along the observable path of Mrk421 is negligeable compared to the other uncertainties. The preliminary estimate of the overall systematic uncertainty is 40% and is still under study.

5 Results

The ON-OFF results on the two blazars after analysis cuts are summarized in the following table.

Source	ON	OFF	ON-OFF	σ	S/B (%)
Mrk421	197541	190254	7287	11.7	3.8
Mrk501	58074	57224	850	2.5	1.5

5.1 Mrk421

The γ-ray origin of the signal observed on Mrk421 has been clearly established by comparing data from flaring periods like January 2000 with those of quiet periods like December 1999, using CAT to monitor the AGN activity. The hypothesis that the ON-OFF excess would be due to the 6.1 magnitude star in the ON source field has been ruled out (Holder (2001), de Naurois (2001)). Correlation studies of the ON-OFF difference with the pointing direction or with the order during the night showed no bias.

The nightly averaged light curve of Mrk421 is given in figure 2. The mean number of ON-OFF run pairs per night is 3.5, that is 1 hour ON source. The plotted value is the integrated flux above 60 GeV calculated by normalizing an E^{-2} differential spectrum to give the observed number of events once multiplied by the acceptance and integrated. The excess rate after analysis is $3.9\ \gamma/minute$. The resulting mean flux is $0.7 \pm 0.3.10^{-9}\ \gamma.cm^{-2}.s^{-1}$. For comparison, the excess rate on the Crab Nebula is $4.4\ \gamma/minute$ and the corresponding flux is $0.6 \pm 0.3.10^{-9}\ \gamma.cm^{-2}.s^{-1}$ with the same analysis.

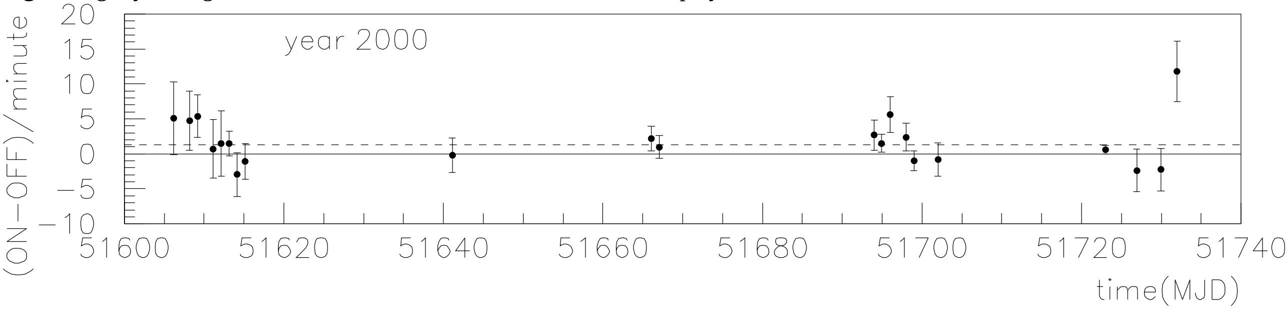
5.2 Mrk501

An excess of 2.5σ has been detected on Mrk501 during the year 2000. The nightly average ON-OFF difference curve is shown on figure 3.

The mean value of this excess is $1.0\ minute^{-1}$.

A flux estimate or an upper limit cannot be made on this source because of the presence of a not yet understood seasonal systematic bias which affects the hadronic background trigger rate. This bias causes the average trigger rate to decrease monthly between the end of Winter and Summer. The magnitude of the effect is 40%. Since the Mrk421 observations have been taken mostly in Winter, their data don't exhibit this effect. However, in Mrk501 data the ON-OFF difference shows no evident correlation with the trigger rate.

Fig. 3. Nightly average ON-OFF difference for Mrk501. Error bars display the statistical errors. The dashed line is the mean value.



6 Perspectives

Since the overall detection reaches 11.7 σ on Mrk421, each flare can be studied independently. More promising perspectives lie in CAT - CELESTE simultaneous data. On one hand, the run by run correlation will allow us to study the variability of the source with more statistics than in Holder (2001). On the other hand, there is now the possibility to extend CAT spectra to the 60 GeV range, which will allow us to locate for the first time the high energy peak of this source.

Our next priority blazar targets after Mrk421 and Mrk501 are 1ES0219+42.8 and 1ES2344+51.4, which are likely to be detectable by CELESTE at 60 GeV according to simple SSC models. 1ES0219+42.8, also named 3C66A, is a radio selected BL Lac object located at z=0.44, i.e. much more distant than Mrk421 and Mrk501. It is also located in the error box of a -2.37 spectral index EGRET source which exhibited a strong 2 day flare in the sub-GeV range (Wallace, 2000). 1ES2344+51.4 was detected by the Whipple observatory in 1995 (Catanese, 1998). A few hours of data have already been collected on both sources.

7 Conclusion

CELESTE is now taking data regularly on AGN. The detector and analysis acceptance versus pointing direction has been established, allowing variability studies. Mrk421 data might be rich in information concerning variability and wide wavelength range spectroscopy, mainly through CAT-CELESTE simultaneous analysis, which is undergoing. There is some indication for a signal on Mrk501.

1ES0219+42.8 and 1ES2344+51.4 will be further observed next year. Our blazar observation strategy is now to focus on these sources while arranging observation schedules in order to take as much data as possible simultaneously with CAT.

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