Estimation of high-state rates from collected VHE and archived ASM data

Martin Tluczykont

September 29, 2006

1 Introduction

Objects such as Active Galactic Nuclei (AGN) exhibit strong flux state variations. The observed very high energy (VHE) gamma-ray emission from AGN is often correlated to their X-ray emission. This correlation can be easily explained with leptonic models such as homogeneous time-independent one-zone SSC models. Even though a hadronic origin of the observed signals cannot be ruled out, leptonic acceleration mechanisms are favoured to explain the observed broad band emission. The detection of neutrinos from these objects would prove the existence of a hadronic contribution to the observed VHE-signals. In the frame-work of multi-messenger strategies (aiming at combining electromagnetic and neutrino data to improve the detection chance for neutrinos) the phenomenology of lightcurves in the electromagnetc wavelength band can give valuable input. In the case of the target of opportunity strategy [Bernardini (2005)] the average observed high-state rate $\mathrm{R_{HS}}$ is of importance. $\mathrm{R_{HS}}$ is defined as the ratio of the time $\mathrm{T_{high}}$ to the time $\mathrm{T_{low}}$ a given object is above/below a certain flux threshold, $\mathrm{R_{HS}} = \mathrm{T_{high}}/\mathrm{T_{low}}$. For a given object, a neutrino event simultaneously observed to a VHE high-state is most likely an atmospheric neutrino coincident with a gamma-ray outburst. However, several such coincidences might also be evidence for a hadronic nature of the VHE high-state and a cosmic origin of the neutrino. The probability for a random coincidence depends on the high-state rate. Thus, $\mathrm{R_{HS}}$ is needed to estimate the significance of the hadronic nature of such coincidences. Different methods for the analysis of lightcurves in different wavelength bands are currently under study. An analysis based on the *maximum likelihood block* method was presented by [Resconi (2006)]. Recently, a large data set was collected from the major VHE gamma-ray experiments [Tluczykont et al.(2006)][1]. These data were combined into single long-term lightcurves and a simple analysis was used to estimate the VHE high-state rate for different flux thresholds. The resulting lightcurve of the blazar Mrk 421 above 1 TeV that spans observation periods from the year 1992 to 2006 (an unprecedented long time period in the VHE regime) is shown in Figure 1.

2 Correlation of VHE Gamma-Rays with X-Rays

Up to now, correlation studies between VHE gamma-rays and X-rays were primarily made using homogeneous data sets from only one VHE-experiment. In this work, all collected VHE data [Tluczykont et al.(2006)] are used along with data extracted from the ASM database web interface at MIT[2] to estimate the correlation relation between VHE flux above 1 TeV and the observed count rate in the ASM X-ray band. In Figure 2, the daily averaged ASM count rate $\mathrm{F_{ASM}}$ versus the daily averaged VHE flux $\mathrm{F_{VHE}}$ is shown. A large scattering of the data points is observed. This is at least partly due to the fact that observations in both observation bands are averaged over one day and are not strictly simultaneous. A profile of the data shows an average linear correlation up to flux levels of around 4 Crab. Above this flux value, some deviations from the linear relation are seen. However at these higher flux levels the statistics is low and the VHE data are biased towards high flux states because of external- and self-triggering on high-states. On some days high fluxes were observed in one wavelength band without aparent counterpart in the other. Such events were previously referred to as orphan or anti-orphan flares. However, as mentioned before, the fluxes are averaged over one day. Therefore, observations are not always strictly simultaneous and sub-day variations can easily explain the observed discrepancies.

---

[1] *archived http://www-zeuthen.desy.de/multi-messenger/GammaRayData/*

[2] *http://xte.mit.edu/ASM_lc.html*

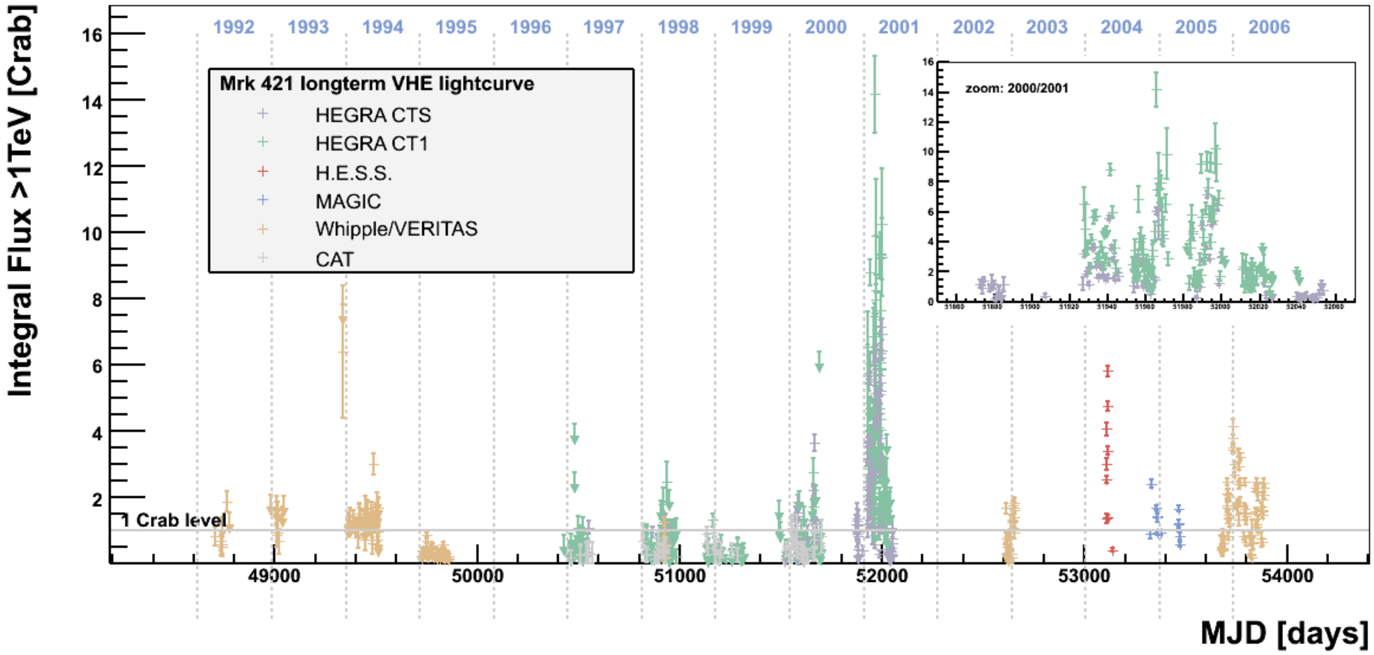

Figure 1: *Long-term lightcurve of Mrk 421. Data from the major gamma-ray telescopes were combined and normalized to the same energy threshold and converted to Crab units (see text).*

3 Distributions of Flux States

3.1 The Observations

In Figure 3, the distributions of the daily averaged flux states of Mrk 421 as observed by VHE experiments and by the ASM are shown. A fit of an exponential in the region of good linearity as given by Figure 2 is made to both distributions. The resulting slopes of the fitted exponentials are compatible within statistical errors, i.e. the two distributions are similar as expected in case of a linear correlation between both flux state populations. For the distribution of VHE flux states only fluxes with significances above $2\,\sigma$ were used. For the ASM distribution all count rates, including negative values, were used. At low flux states respectively count rates, detector sensitivity effects become important. Further, the VHE distribution is biased towards high flux states (self- and external-triggering on high-states), whereas the ASM count rate distribution represents a random sampling of the object activity.

3.2 The Interpretation

The distribution of ASM count rates can be described by a Gaussian detector-noise distribution, a population of low count rates interpreted as a baseline flux and an exponential tail representing the population of stochastic outbursts of the object. In Figure 4 these different components are shown. One has to note that the observed distribution is the true distribution folded with the detector acceptance. Therefore, at low count rates the distribution is strongly dominated by systematic effects (detector threshold). The true baseline – if existent at all – might be lower. Due to their comparatively low statistics and intrinsic observation bias the VHE observations are less accurate than the ASM data when deriving any properties from them. Due to the linear correlation between daily averaged X-ray and VHE gamma-ray fluxes one would, on average, expect equally shaped flux distributions in both wavelength bands. Therefore, the better statistics and representative (random) character of the X-ray monitor measurement can be used to derive generic properties of the observed objects. Thus, assuming this correlation is true, the conclusions made from the ASM data also on average hold true for the VHE band and can thus be used to verify the results of the analysis of the VHE data.

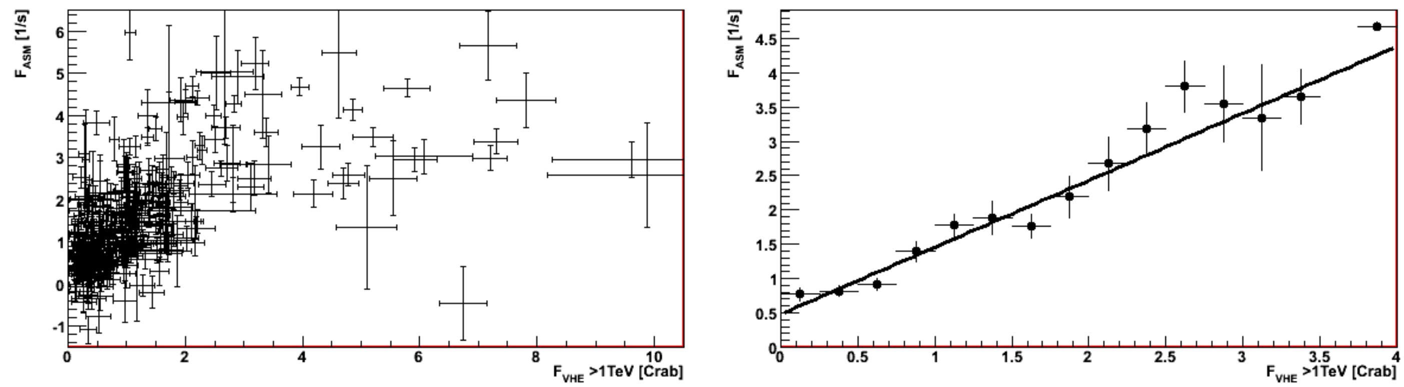

Figure 2: *VHE fluxes* $\mathrm{F_{VHE}}$ *versus ASM count rates as a scatter plot (left) and as a profile histogram of the high statistics region including a fit of a 1st-order polynomial (right). The high VHE fluxes without correspondingly high ASM flux cannot necessarily be qualified as orphan-flares because the fluxes and count rates are averaged over one day and are not necessarily simultaneous. For the same reason a large scatter is observed in the left plot.*

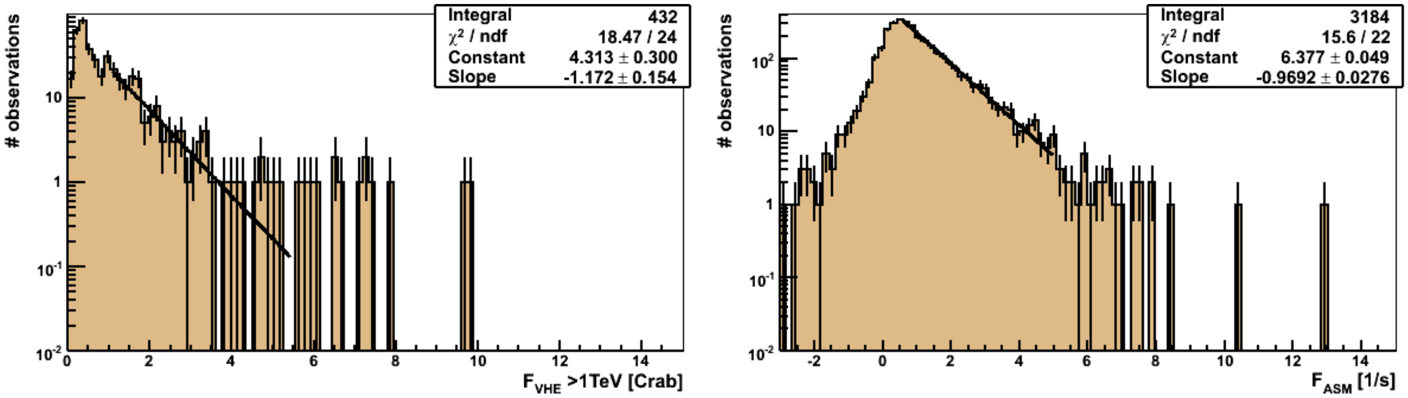

Figure 3: *Distribution of VHE flux states (left) and ASM count rates (right) of Mrk421. Exponentials are fitted in the regions without detector threshold effects and good linear correlation between both observation bands.*

4 Extracting a High State Rate $\mathrm{R_{HS}}$

Adopting the interpretation of the previous section that the exponential shape of the flux state distribution reflects the population of outburst flux states of the object, one can easily derive an average high-state rate from the observed exponential distribution of the ASM count rates or from the exponential distribution of the VHE flux states. The relative high-state rate for a given threshold flux $\mathrm{F_{thr}}$, $\mathrm{R_{HS}(F_{thr})}$ is given by

$$\mathrm{R_{HS}(F_{thr})} = \frac{\int_{\mathrm{F_{thr}}}^{\infty} \mathrm{e^{bx}dx}}{\int_{\mathrm{F_0}}^{\infty} \mathrm{e^{bx}dx}} = \frac{\mathrm{e^{bF_{thr}}}}{\mathrm{e^{bF_0}}}$$

where $\mathrm{F_0}$ is the true baseline flux of the object and b is the slope of the flux distribution. The mean of the Gaussian describing the baseline flux in Figure 4 can be chosen for $\mathrm{F_0}$. The resulting average relative high-state rates for different flux thresholds ($\mathrm{F_{thr}}$) are shown in Figure 5. If the true baseline flux is actually lower, the estimation of $\mathrm{R_{HS}}$ has to be interpreted as an upper limit on the acutal high-state rate. This is also the case if an unresolved flux-state component exists that is not accessible by the experiment, e.g. a large population of very low baseline fluxes that are not accessible by the detector. One has to note that $\mathrm{R_{HS}}$ is averaged over the complete observation period. As a matter of fact the ovservations rather indicate that the probability for an outburst is higher if an outburst was observed one day before, i.e. longer periods of high states are observed. Therefore $\mathrm{R_{HS}}$ cannot be translated into a high-state probability for any given

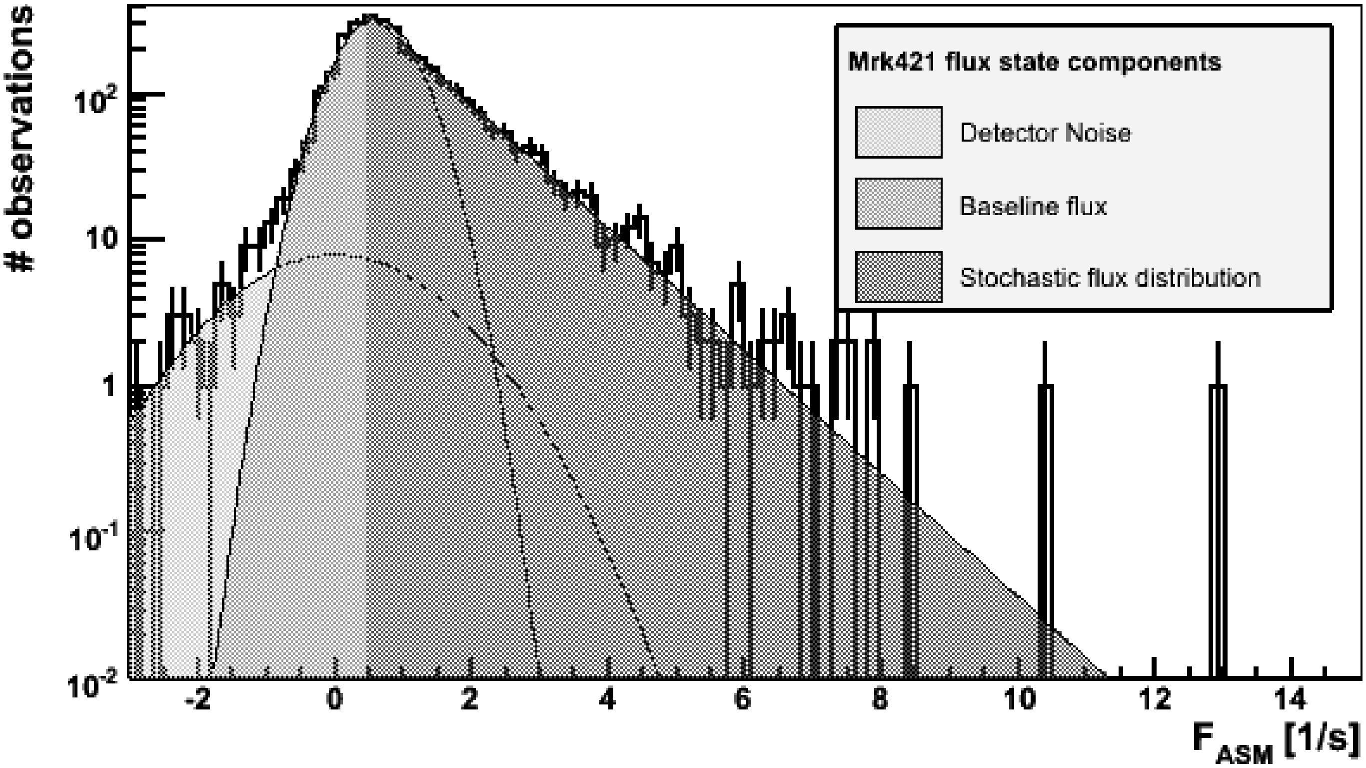

Figure 4: *The distribution of flux states of Mrk421 as measured by the ASM can be interpreted as a baseline described by a Gaussian (medium grey) and a stochastic outburst distribution described by an exponential (dark grey). An additional Gaussian describes a very low level of detector noise (light grey) that does not affect the overall distribution at higher fluxes. Note that due to detector acceptance effects the true baseline might be lower than the observed one. For each Gaussian area the corresponding curve is shown as a thin line.*

day but rather as an average probability to observe the object in a high state without knowledge about its previous flux state.

5 Summary & Outlook

It was shown that the observed daily averaged flux states of Mrk 421 above 1 TeV show a linear correlation with the daily averaged ASM count rates (X-rays) in the region up to 4 Crab. Beyond this flux level some deviations from a linear correlation are seen. However, this deviation is not significant since it can be explained by the fact that the data are averaged and not totally simultaneous and that the VHE data are biased towards higher flux levels.

It is possible to derive the relative high-state rate of AGN from the slope of the observed flux state distributions of the VHE and ASM observations. Under the assumption that a linear correlation is true, the VHE and ASM distributions are expected to show the same exponential slope, which is actually observed. The results are good estimates of the average high-state rate and are robust upper limits in case the interpretation of the baseline flux is not accurate.

R_{HS} can be estimated for all objects for which enough ASM data is available. Under the assumption that a correlation also exists for these other objects, the rate estimated from the ASM data would be the actual rate in the VHE regime. Wether this method can be applied to other objects will be investigated. The ASM is a low-sensitivity all-sky monitor experiment and might not be the best instrument for such a study. Dedicated multiwavelength campaigns were carried out with the PCU onboard RXTE and VHE gamma-ray experiments. More accurate correlation studies should be possible with these data and are planned [Resconi et al.(2006)] Results will be shown at the upcoming collaboration meeting at Zeuthen. Further, toy Monte-Carlo simulations modelling high-state distributions are planned.

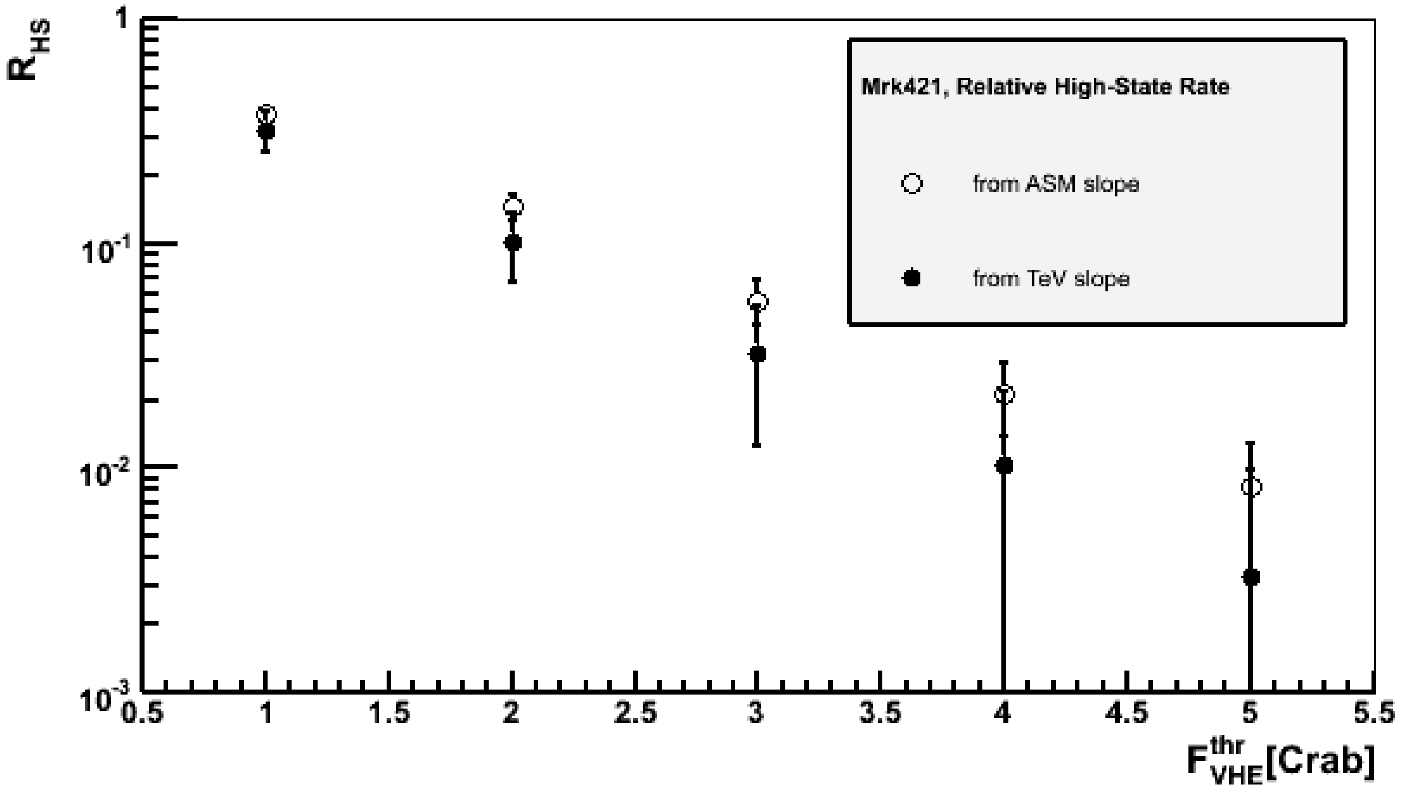

Figure 5: *The average relative high-state rate as estimated from the flux state distributions of VHE data (filled circles) and ASM data (open circles).*

References

[Bernardini (2005)] Bernardini, E., in 'Towards a Network of Atmospheric Cherenkov Detectors', Palaiseau, 2005

[Resconi (2006)] Resconi, E., TeV Particle Astrophysics, Madison, 2006

[Tluczykont et al.(2006)] Tluczykont, M., Shayduk, M., Kalekin, O., Bernardini, E., *Long-term Gamma-Ray lightcurves and high-state probabilities of Active Galactic Nuclei* To be published in the Proc. of *TeV Particle Astrophysics*, Madison, 2006

[Resconi et al.(2006)] Resconi, E., private communication