Gamma-ray halo around 3C 279: looking through the Sun on the 8th of October

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ABSTRACT
We discuss how the solar occultations of bright sources of energetic gamma rays can be used to extract non–trivial physical and astrophysical information, including the angular size of the image when it is significantly smaller than the experiment’s angular resolution. We analyze the EGRET data and discuss prospects for other instruments. The Fermi Gamma Ray Space Telescope will be able to constrain the size of a possible halo around 3C 279 from observations it makes on the 8th of October each year.

Key words: gamma-rays: theory.

1 INTRODUCTION

The brightest source in the sky almost at any wavelength, the Sun is very weak in high-energy ($E \gtrsim 100$ MeV) gamma rays. This property can be used to study solar occultations of gamma-ray sources.

The width of the point-spread function (PSF) of telescopes detecting photons at these energies is quite large, of order several degrees. The enormous exposure of the Fermi Gamma Ray Space Telescope (the telescope previously known as GLAST) would partially compensate for the poor resolution; however, it would be almost impossible to directly measure the angular size of the image which may be smaller than the PSF width. On the other hand, energetic gamma-ray images of distant sources may indeed have a significant angular size due to the cascading of photons on the background radiation and magnetic deflections of the cascade electrons and positrons. It has long been known that one can obtain the angular size of stars from lunar occultations, we suggest that one may determine the image size of gamma-ray sources screened by the Sun.

The simplest and most direct effect of an extended image size would be the detection of flux from the source during occultation. Such a result could also be the signal of the transparency of the Sun to gamma rays possible in several scenarios of new physics (Fairbairn, Rashba & Troitsky 2007); however the parameter space of particular models is strongly disfavoured by results of other experiments (e.g. Andrianonie et al. 2007).

In Sec. 2 we review our analysis of archival EGRET data of the 1991 occultation of 3C 279 during which a non-zero flux was indeed observed, although at a very low statistical significance.

With a sensitive enough telescope, a more detailed study of the light curve during ingress and egress would be possible. In Sec. 3 we discuss the potential of Fermi for this kind of a study and mention sources other than 3C 279 while Sec. 4 summarizes our conclusions.

2 POSSIBLE MECHANISMS FOR EXTENDED EMISSION

Very high energy photons interact with other photons in the source, with photons along the path between the source and the earth and with photons near to the Sun. These interactions result in the production of electrons and positrons...
which themselves consequently interact with the gamma-ray background leading to the development of electromagnetic cascades which result in a gradual decrease of the average energies of propagating photons. Ambient magnetic fields deflect the electrons and positrons and, as a result, the image of the source seen in gamma rays becomes extended. This kind of extended image may be observed for distant sources which emit very energetic photons (both the Universe and typical source environments are transparent for gamma rays below ~ 1 GeV). Recently, the MAGIC collaboration has reported (Teshima et al. 2007) the detection of $E > 200$ GeV emission from 3C 279. Given the expected absorption on the cosmic infrared background, this corresponds to an extremely high luminosity of the quasar at very high energies (Albert et al. 2008). Moreover, according to both the Hillas criterion (Hillas 1984) and to bounds on the source parameters from energy losses (see e.g. Ptitsyna & Troitsky 2008), the jets of 3C 279 might provide the necessary conditions for the acceleration of cosmic rays (CR) up to ultra-high energies (UHE), $E > 10^{19}$ eV. 3C 279 therefore seems to be an ideal candidate to search for an extended halo due to the production of secondary photons.

Let us summarize briefly a few different scenarios which could lead to the formation of an extended image:

**Inverse Compton effect in the source environment ($\lesssim$ GeV).** It has been pointed out some time ago (Aharonian, Coppi & Volk 1994) that a halo of (sub-)GeV inverse-Compton photons may form around the source of very high energy gamma rays. The estimates of (Aharonian, Coppi & Volk 1994) for the case of 3C 279 give rise to an expected angular size of the halo of $\sim 0.2\degree$ and a flux from the halo approximately equal to the flux coming from the central point source.

**Synchrotron halo of UHECR sources ($\sim$GeV).** For reasonable values of the magnetic field ($\lesssim 10^{-9}$ G) around a source of UHECR, synchrotron photons contribute to a halo of angular size of a fraction of degree potentially detectable by Fermi (Gabici & Aharonian 2007; Atoyan & Dermer 2008).

**Electromagnetic cascades on the intergalactic magnetic fields ($\sim 10^3$ GeV).** Energetic photons from distant sources undergo electromagnetic cascades when scattering off extragalactic background light, resulting in extended images for TeV sources (Neronov & Semikoz 2007). Even stronger cascading is expected for secondary photons from UHECR sources (see e.g. Ferrigno, Blasi & De Marco 2003): because of their higher energies, they can scatter on CMB photons as well as the infrared background, and the number density of CMB photons is much higher. However, extended emission of this kind is too weak at GeV energies to lead to a detectable effect.

**Electromagnetic cascades on the solar radiation ($\sim 10^2$ GeV).** The solar radiation is strongly concentrated in the optical band, corresponding to the thermal emission of 5800 K, that is $\omega_{\text{Sun}} \sim 1$ eV. The pair production threshold is determined by $E = m_e^2/\omega_{\text{Sun}} \approx 260$ GeV. The optical depth of the solar radiation with respect to the pair production for 260 GeV photons tangent to the solar surface is $\tau \sim 0.1$ and any secondary electrons and positrons produced in this way would be isotropized by the $\sim 1$ G magnetic field of the sun. Because of this, the extended halo as viewed from earth would be too weak to be observable (one may hope to detect such a halo when the Sun passes in front of the regions with significant diffuse emission at 260 GeV if such regions exist, but without the timing signature, this emission would be hard to detect).

Formation of the halo is a random process and therefore one expects that the variability timescale of the halo should be determined by its physical size (light minutes for the solar neighbourhood but millions of light years for all other scenarios).

We see that one might expect a halo around 3C 279 in the energy band detectable by EGRET and Fermi (above 100 MeV). This halo is of angular size $\sim 0.1\degree$ while the point-spread function (PSF) of these instruments extends for several degrees. However, the halo could be detected when the Sun screens the bright central source. Study of the shape and spectrum of this halo would help to distinguish between various scenarios of its formation and therefore contribute to our understanding of the source engine, the source environment and the extragalactic background radiation. The extended halo would reveal itself in a smooth falling of the flux when the Sun approaches the source and in a non-zero flux from the source while it is screened by the Sun. In Fig. 1 we present examples of the lightcurves for various source extensions.

![Figure 1. Normalized light curves of an extended source occulted by the Sun, assuming Gaussian model for the extended image. Different values of the radial source variance $\sigma$ are taken in units of degree. The time corresponds to the angle (in degree) between source center and the point of its minimal separation from the center of the solar disk, for the minimal separation of $0.20\degree$. The shadow region represents the occultation of the point-like source.](image-url)

### 3 EGRET OBSERVATIONS

In 1991, the solar occultation of 3C 279 occurred within the field of view of EGRET. We have analysed publicly available EGRET data to test the conjecture that the flux from the quasar was non-zero when the source was screened by the Sun (Fairbairn, Rashba & Troitsky 2007); here we present more details and discussions related to the study.

Given the coordinates of 3C 279 taken from the NASA/IPAC Extragalactic Database (NED) (http://nedwww.ipac.caltech.edu) and the coor-
To determine the source flux, one compares the distribution of arrival directions of detected gamma-rays with the sum of background and point-source fluxes using a particular model for the former and the instrument point-spread function (PSF) for the latter, both convolved with time- and direction-dependent experimental exposure. We denote the diffuse background flux of gamma rays from a given direction \((\alpha,\delta)\) as \(B(\alpha,\delta)\). This flux was determined by Cillis & Hartman \(2003\) from the analysis of the EGRET data. From \(B(\alpha,\delta)\), we calculate \(B(\psi)\), the expected flux of background photons within the angular distance \(\psi\) from the source we study (it is the integral over the corresponding circle on the sky, of \(B(\alpha,\delta)\) weighted by exposure). The PSF of EGRET, obtained by its careful calibration \(\text{Thompson et al. 1993}\), is energy dependent; one has to assume some spectral index \(p\) for the source. We use the PSF for \(E > 100\) MeV and \(p = 2\) (the EGRET-measured spectral index of 3C279 is 1.96 ± 0.04 \(\text{Hartman et al. 1999}\)) from Cillis & Hartman \(2003\) and denote it as \(p(\psi)\).

The number \(n(\psi)\) of observed photons from the circle of angular radius \(\psi\) centered at the source (a ladder-like function of a single variable \(\psi\)) is fitted by the sum of a slowly varying background and a sharp PSF,

\[ n(\psi) = bB(\psi) + N_\psi p(\psi) + \sum_i s_i(\psi), \]

where \(b\) and \(N_\psi\) are parameters of the fit (determined by the standard least-squares method). Following the original 3EG procedure, Mattox et al. \(1996\), we keep the coefficient \(b\) free motivated by possible temporal variations of the background and \(s_i\) are contributions of known nearby sources (for which we use the 3EG values for this viewing period). The best-fit number of source photons \(N_\psi\) divided by the exposure determines the source flux. In the same way as the authors of the 3EG catalog, we select events with energies \(E > 100\) MeV, TASC in coincidence at 6 MeV and distance to the source not exceeding 15°. These cuts correspond also to the PSF we use.

Our approach is very similar to that used for the construction of the 3EG catalog (see Mattox et al. \(1996\)) for more details of the method) apart from some details:

1. We use the updated maps of EGRET-observed diffuse background \(\text{Cillis \& Hartman 2003}\) while Hartman et al. \(1999\) used a theoretical model for the distribution of the background flux.
2. The catalog construction used the counts distribution binned in two celestial coordinates; we use the unbinned distribution in one coordinate — distance from the source (both approaches were discussed by Mattox et al. \(1996\)). This is more appropriate in the case of small number of observed events.
3. The 3EG procedure substracts all 3-sigma sources (in the catalog, they list only 4-sigma ones). We substract only the sources listed in the catalog, even if they are fainter than 4-sigma for this particular viewing period (in this way, we potentially exclude some sources which did not pass the 4-sigma cut for this viewing period, or for any other viewing period or their sum, but were brighter than 3-sigma in this period).

We performed the fit for the occultation period and for the rest of the viewing period. The best fits give the signal of \(N_\psi = 4.82\) photons for the occultation and \(N_\psi = 284.5\) for the rest of the viewing period. Within the 68% containment angle of the PSF, the numbers of signal and background photons are roughly equal. Therefore we found some weak evidence for a non-zero point-source flux from the location of 3C279 during the occultation, \(6.2_{-2.0}^{+3.3}\) \(f \text{cm}^{-2} \text{s}^{-1}\), to be compared with the value obtained from the analysis of the rest of the same viewing period, \(8.6 \pm 0.5\) \(f \text{cm}^{-2} \text{s}^{-1}\) (the value quoted in the 3EG catalog for this period is \((7.94 \pm 0.75) \cdot 10^{-7} \text{cm}^{-2} \text{s}^{-1}\), the zero flux (point-like source) is excluded at \(\approx 98\%\) confidence level (CL); no upper limit can be placed on the source extension because unsuppressed flux is well within the 68% CL error bars. Assuming a Gaussian extended image, the best fit for the radial extension is \(\sigma \approx 0.283\). The error bars in Fig. 2 give an idea of the size of statistical uncertainties both of this result and of potential future studies.
Here we mention some possible subtleties which one should be aware of when trying to understand this result or similar future observations.

Other nearby 3EG sources. The numbers quoted above were obtained with the subtraction of the expected contribution of a single nearby source detected at 3 sigma in the v.p. 11.0 (3EG J1235+0233, see the list of nearby sources in Table 1). The result can in principle be confused by contribution of other sources. As a test, we changed the 3-sigma threshold adopted by EGRET to both 2 sigma and to 4 sigma without any significant change in the result. The procedure described above assumed that the flux of the sources being subtracted was constant during the viewing period. Clearly, an extreme flare of 3EG J1246–0651, or 3EG J1310–0517, or both, exactly at the occultation time, could explain our result without 3C 279. Note however that on the time scale between one viewing period and another, these sources do not demonstrate significant variability so such a flare seems unlikely.

The Sun. The solar surface could be a gamma-ray source due to its interaction with cosmic rays. Early EGRET studies put a 95% C.L. upper limit of 2.0 × 10^{-7} cm^{-2} s^{-1} on the flux of the quiet Sun (Thompson et al 1997). A marginal detection of solar disk flux \sim 4 \times 10^{-8} cm^{-2} s^{-1} has been reported by Orlando & Strong (2008). The theoretical expectation of the flux of the disk of the quiet Sun is about 2 \times 10^{-8} cm^{-2} s^{-1} (Orlando, Petry & Strong 2007). The extended emission of the Sun (Moskalenko, Porter &Digel 2006; Orlando & Strong 2007, 2008) cannot explain the observed excess: within the 68% containment width of the EGRET PSF the expected flux from the extended solar emission is about \sim 1.5 \times 10^{-7} cm^{-2} s^{-1} assuming the model for the solar extended flux and the total flux of 4.44 \times 10^{-7} cm^{-2} s^{-1} obtained by Orlando & Strong (2008) in the 10-degree circle around the Sun. We would like to note that the recent unpublished Fermi observations have been used to extract the solar flux from the 10^5 region around the Sun which is (4.59 \pm 0.89) \times 10^{-7} cm^{-2} s^{-1} (Brigida 2009), in a good agreement with Orlando & Strong (2008). This flux is low compared to that of 3C 279 and may be neglected within our current poor precision.

| 3EG name | other name | \( \theta \) | \( F_{-7} \) | \( (TS)^{1/2} \) |
|----------|------------|----------|----------|----------|
| 1219−1520 | 3C 279 | 13.2° | <0.89 | 0.0 |
| 1229+0210 | 3C 273 | 10.5° | <0.95 | 0.4 |
| 1230−0247 | 1229−021 | 7.0° | 1.13±0.43 | 2.9 |
| 1234−1318 | | 9.3° | <0.89 | 0.0 |
| 1235+0233 | | 9.9° | 1.24±0.41 | 3.5 |
| 1236−0457 | | 11.9° | <0.90 | 0.3 |
| 1246−0651 | 1243−072 | 2.5° | 1.29±0.54 | 2.7 |
| 1310−0517 | | 3.6° | 1.05±0.51 | 2.2 |
| 1339−1419 | 1334−127 | 13.6° | <1.08 | 0.0 |
| 1255−0549 | 3C 279 | 0.0° | 7.94±0.75 | 15.1 |

Table 1. Potential confusing sources: 3EG sources within 15° of 3C 279. \( \theta \) is the angular offset from 3C 279; \( F_{-7} \) is the flux during v.p. 11.0 in 10^{-7} cm^{-2} s^{-1}, (TS)^{1/2} is the significance of detection in the v.p. 11.0. Data from Hartman et al. (1999).

**Solar flares.** Solar flares are sources of gamma rays; the BATSE records list four weak flares in the occultation time (see Table 2). The photons detected by EGRET during these flares were separated from the Sun by at least 10.8°, so they most probably do not contribute to the point-source flux (the 68% width of the EGRET PSF at \( E > 100 \) MeV is 3.3°).

The Moon. One more gamma-ray source was nearby during the time of these EGRET observations: the Moon was in 6° to 9° from the Sun during the period of interest. The gamma-ray (\( E > 100 \) MeV) flux of the Moon in 1991 was (3.6 ± 0.9) \times 10^{-7} cm^{-2} s^{-1} (see Fig. 2 of Thompson et al. 1997). Given the separation, the PSF width and the flux we conclude that the lunar contribution cannot explain the observed excess.

Possibility of misidentification. Though 3C 279 is considered as one of the best EGRET identifications, one still cannot exclude the possibility that the gamma-ray excess is due to a source mis-identified with 3C 279. This would-be actual source, if located just 20 arc min away, would not be screened by the Sun. The best-fit position of the EGRET source associated with 3C 279 is indeed displaced from the position of the quasar as seen in other wavelengths, but this position is even more deeply screened by the Sun during an occultation.

| Start, UT | End, UT | EGRET photons (separation from the Sun) |
|----------|--------|----------------------------------------|
| 20h14m | 20h15m | 27.2°, 32.3°, 21.7°, 19.4°, 17.8° |
| 20h48m | 20h49m | – |
| 21h59m | 22h00m | 10.8° |
| 22h07m | 22h08m | – |

Table 2. Solar flares during the occultation.

4 PROSPECTS OF FUTURE OBSERVATIONS

Let us estimate the ability of new experiments to observe the solar occultations of gamma-ray sources, notably that of 3C 279. AGILE cannot be pointed to the Sun because of configuration of its solar panels (M. Tavani, private communication). Atmospheric Cerenkov telescopes cannot be pointed at the Sun as they would be destroyed. The sensitivity of MILAGRO is insufficient to detect the source in 8.5 hours. The Large Area Telescope (LAT) of Fermi may however be used to observe the occultation successfully.

In the survey mode, Fermi will scan the sky rotating continuously, so the short-period exposure to a given point in the sky is not too large. The sensitivity may be estimated using the Fermi web service (http://www-glast.slac.stanford.edu/software/IS/glast_performance.html) For the pointing mode, the average on-axis effective area for \( E > 100 \) MeV, weighted with the ~ \( E^{-2} \) spectrum, is \sim 4700 cm^2. Further precision may be gained by repeating the observation each year.

To estimate the ability of the instrument to detect non-zero flux during the occultation, we have to assume a particular value of the total flux of the source. 3C 279 is strongly
Solar occultation of 3C 279 in gamma rays

5 CONCLUSION

It will be interesting to try and measure the angular sizes of images of energetic gamma-ray sources by means of observation of their solar occultations. The best target is 3C 279, whose occultation happens each year on the 8th of October. EGRET observations made during such a period did not exclude the unsuppressed flux of the quasar when it was screened by the Sun. The sensitivity of the Fermi telescope is high enough that if the flux was unsuppressed during occultation, it could be observed more definitively than with EGRET. Fermi can also constrain the angular size of the image even in the survey mode, and is capable of obtaining a light curve by the combination of several observations in the pointing mode. This would help to constrain models of particle acceleration and magnetic fields in and around the quasar. If the flux during the occultation exceeds the non-variable flux of the source (as it is slightly favoured by the EGRET data), it would mean that either the extended image is formed relatively nearby or the Sun is partially transparent for the point-like gamma-ray emission (both options would mean a discovery of some unconventional physical or astrophysical phenomenon). The same method may be applied to refine the coordinates and/or to estimate the angular size of images of other gamma-ray sources screened by the Sun.

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Table 3. (EGRET and FERMI gamma-ray sources potentially eclipsed by the Sun. $b_e$ gives the ecliptic latitude calculated from the FERMI bright source list [Abdo et al. 2009]. “GEV” means $E > 1$ GeV detection by EGRET [Lamb & Macomil 1997]. “VHE” means $E > 100$ GeV detection.

| name               | $b_e$ | 3EG  | GEV  | VHE |
|--------------------|-------|------|------|-----|
| AX J1809.8–2333    | −0.099| J1899–2328 | yes | no  |
| 3C 279             | +0.186| J1255–0549 | yes | MAGIC |
| W28=M20 (?)        | −0.020| J1800–2338 | yes | HESS |

Two more EGRET sources with ecliptic latitudes $b_e < 0.25^\circ$ (see Table 3) had been classified as unidentified in the 3EG catalog. Further studies suggested potential identifications; they also have been detected by FERMI [Abdo et al. 2009]. The study of the solar occultation may help to determine their coordinates with higher precision, testing the identification. We expect that these (and maybe other) sources will become potential targets for angular-size measurements.

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