Constraining the extension of a possible gamma-ray halo of 3C 279 from 2008–2014 solar occultations

Egor Kotelnikov,1 Grigory Rubtsov2 and Sergey Troitsky2

1Physics Department, M.V. Lomonosov Moscow State University, Vorobjevy Gory, 119991 Moscow, Russia
2Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect 7a, 117312 Moscow, Russia

ABSTRACT
The angular extension of the gamma-ray image of 3C 279 may be constrained by studying its solar occultations as suggested by Fairbairn et al. We perform this kind of analysis for seven occultations observed by Fermi-LAT in 2008–2014, using the Fermi-LAT SOLAR SYSTEM TOOLS. The results are interpreted in terms of models with extended gamma-ray halo of 3C 279; first constraints on the size and the flux of the halo are reported.

Key words: magnetic fields – quasars: individual: 3C 279 – gamma-rays: general.

1 INTRODUCTION

Some time ago, it was pointed out (Fairbairn, Rashba & Troitsky 2007) that one of the brightest gamma-ray sources in the sky, blazar 3C 279, is screened by the Sun every year. Since the Sun is not a very bright source of photons with energies $\gtrsim 100$ MeV, these events look as occultations and may be used to constrain some new models of physics and astrophysics. In particular, an extended halo of the source, if exists, would shine beyond the solar disc while the central point source is screened. Measurements of the gamma-ray flux of 3C 279 during the occulation may constrain (Fairbairn, Rashba & Troitsky 2010) the size and the flux of the extended halo in a way similar to the early measurements of angular diameters of stars in their lunar occultations, with the precision exceeding the angular resolution of the instrument.

Recently, the Fermi-LAT collaboration has performed (Barbiellini et al. 2014) an analysis of four (2008–2011) solar occultations of 3C 279 and constrained the source flux during the periods when its centre was screened. Barbiellini et al. (2014) have considered and constrained two scenarios: (i) transparency of the Sun for gamma rays and (ii) an extended sharp-edged disc with constant surface brightness and a priori fixed energy-dependent radius of $1.5 \times (E/500\text{MeV})^{-1}$, where $E$ is the gamma-ray energy. Nevertheless, there is a gap between these interesting results and constraints on realistic models of physics and astrophysics. We note that the solar transparency, case (i), as suggested by Fairbairn et al. (2007), requires an axion-like particle with parameters firmly excluded, since then, by several laboratory experiments, see e.g. Zavattnini et al. (2008), Pugnat et al. (2008) and Ehret et al. (2010).

The extended halo, case (ii), if it exists, should be formed as a result of a random scattering process and is unlikely to look like a sharp-edged constant-intensity disc. The size of the halo is determined by a number of physical parameters of the source and/or of the intergalactic space, notably by the values of the magnetic fields. The halo extension is therefore an important observable to be constrained while it was kept a priory fixed in the analysis of Barbiellini et al. (2014).

In this work, we fill this gap and follow the prescription of Fairbairn et al. (2010) more precisely; namely, we consider the halo size as a free parameter, while the halo shape is taken to be Gaussian. This approach opens a way to study and to constrain various models of the halo formation, as well as physical parameters of the source and the strength of the intergalactic magnetic field; note that the latter is a subject of intense debates. We make use of publicly available Fermi-LAT data for seven occultations (2008–2014) thus almost doubling the statistics as compared to four occultations used by Barbiellini et al. (2014).

2 DATA, ANALYSIS AND RESULTS

In this work, we use the Pass 7REP (V15) data of Fermi-LAT (Atwood et al. 2009). We consider seven solar occultations of 3C 279 which happened on the 8th of October, 2008–2014. The precise periods of the occultations have been calculated with the help of the HORIZONS system (Giorgini et al. 1996). We processed the data with the standard gtlike routine from FERMI SCIENCE TOOLS v9r32p5.1 We use the ‘SOURCE’ class photons with energies greater than 100 MeV. We apply standard quality cuts and require that photon zenith angles with respect to the Earth do not exceed 100° and the satellite rocking angle is smaller than 5°.

Since we are interested in solar occultations, we need to disentangle fluxes of the Sun and of the blazar during the events. The Sun is a gamma-ray source firmly detected by Fermi-LAT (Abdo et al. 2011), with the flux from the solar disc being produced...
by cosmic ray interactions with the solar surface (Morris 1984; Hudson 1989; Sekel, Staney & Gaisser 1991). Another, much more extended, flux component is caused by the inverse Compton scattering of cosmic ray electrons on the solar light (Moskalenko, Porter & Digel 2006; Orlando & Strong 2007, 2008). At the time-scales of the order of a week to a month, the flux of the quiet Sun is stable and may be determined by means of dedicated tools developed by the Fermi group for observations of moving targets, the Fermi-LAT SOLAR SYSTEM TOOLS (Johannesson et al. 2013).

However, the time-scale of an occultation, ~8.5 h, is too short to determine its flux with the required accuracy. We, therefore, choose to study a four-week period surrounding each occultation, to determine the solar flux by means of the Solar system tools. The tools assume that the solar flux is proportional to an average Fermi-LAT solar flux. The spatial-spectral-template of the moving Sun for the given time interval is produced with the gsntemp tool. The template includes the solar disc as well as the extended emission with their energy and direction dependences, while a single parameter, the overall flux normalization, is fitted. A complete model of the sky region includes Sun, Galactic and isotropic diffuse components, 3C 279 and other point sources in the area of interest from the 2FGL catalogue (Nolan et al. 2012). The solar path in the gamma-ray sky is sketched in Fig. 1. The results are given in Table 1, together with 3C 279 fluxes for the same periods, quoted for reference. Then, we use this fixed solar flux in the background model for the short-time observations during the periods when the point source at the position of 3C 279 was screened by the Sun. The flux of 3C 279 during the occultations, obtained in this way, is given in the last column of Table 1. Within the statistical errors, this flux is consistent with zero for each individual occultation, as one would expect for a usual point-like source. In order to achieve better precision, we merge the seven occultations with the following procedure:

(i) the seven photon files corresponding to the particular occultations are used jointly,
(ii) the exposure cubes are co-added with the gsntemp tool,
(iii) the seven extended sources are included in the model, each representing the solar flux and the motion template for a particular year.

A stacked sum of all seven exposures results in a marginal excess of (2.6 ± 1.1) × 10^{-7} cm^{-2}s^{-1}, the 95 per cent confidence level (CL) limit on the observed flux of 3C 279 when it is screened by the solar disc is thus rather weak,

\[ F_{\text{disc}} < 4.8 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{(95 per cent CL)}. \]  

(1)

The best-fitting excess in the stacked occultation result, according to the glike tool, corresponds to \( \approx 22 \) photons from the source while the number of background photons from the Sun is \( \approx 90 \). The stacked solar flux (both for the disc and for the extended emission), obtained in our fits, is (1.02 ± 0.04) times the value of Abdo et al. (2011).

To interpret the flux constraints in terms of the extended image, we simulate photons from a Gaussian extended source with the total flux \( F_{\text{H}} \), centred at the position of 3C 279, with the extension \( \sigma \). The flux density at the angular distance \( \theta \) from the blazar is thus proportional to

\[ \exp \left( -\frac{\theta^2}{2\sigma^2} \right). \]

Then, we take into account the apparent motion of the Sun across the source and calculate the fraction of the simulated photons that are not screened by the solar disc during the occultation, when the central point is behind the Sun. This fraction, \( F_{\text{obs}}/F_{\text{H}} \), is plotted in Fig. 2 as a function of \( \sigma \). By making use of this plot, we

### Table 1. Fluxes (\( E > 100 \text{MeV} \)) of the solar disc and of 3C 279, as determined for \( \pm 2 \) weeks around the occultation, and of 3C 279 during the occultation; see the text for details of the account of the solar background.

| Year | Flux, \( \pm 2 \) weeks, \( 10^{-7} \text{cm}^{-2} \text{s}^{-1} \) | Flux at occultation, \( 10^{-7} \text{cm}^{-2} \text{s}^{-1} \) |
|------|-------------------------------------------------|---------------------------------|
|      | Solar disc                                       | 3C 279                          | 3C 279                          |
| 2008 | 4.6 ± 0.4                                       | 3.6 ± 0.4                       | 2.5 ± 2.6                       |
| 2009 | 5.2 ± 0.5                                       | 7.1 ± 0.6                       | 5.0 ± 5.3                       |
| 2010 | 3.0 ± 0.4                                       | 8.1 ± 0.6                       | 1.7 ± 4.6                       |
| 2011 | 3.2 ± 0.4                                       | 2.6 ± 0.3                       | 0.8 ± 1.5                       |
| 2012 | 4.9 ± 0.4                                       | 2.4 ± 0.4                       | 2.1 ± 2.7                       |
| 2013 | 7.4 ± 0.4                                       | 6.2 ± 0.6                       | 2.0 ± 2.1                       |
| 2014 | 3.9 ± 0.4                                       | 3.8 ± 0.4                       | 5.5 ± 3.1                       |
|      | Stacked                                         | 4.7 ± 0.2                       | 4.0 ± 0.2                       | 2.6 ± 1.1                       |

\( \ast \) One may note that the solar flux quoted for 2013 was considerably higher than in other periods. We have traced the reason for this. Large solar flares, of M class and higher, are confirmed sources of energetic gamma rays, see e.g. Ackermann et al. (2014). The enhancement of the solar flux in the 2013 period corresponds to a series of solar flares between the 2013 October 9 and 13, recorded in the NOAA archive, http://www.solarmonitor.org. Both the detected flares and other unaccounted solar activity may affect systematically the signal and background estimates. We have checked that no flares were detected during all seven occultations and the systematic effect of the 2013 solar flares is within 10 per cent in terms of the final result. We leave the investigation of a more detailed time-dependent solar flux model for future.
Interestingly, the inverse-Compton emission is essentially zero in the direction of the solar disc, thus reducing the background in the searches for this effect (Orlando & Strong 2013). Just outside the disc, the emission from beyond the Sun returns to a significant level, so it is necessary to account for this background in this study.

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