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The Influence of the Sun and Moon on the Observation of Very High Energy Gamma-ray Sources Using EAS Arrays

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Abstract

With great advance of ground-based extensive air shower arrays, such as LHAASO and HAWC, many very high energy (VHE) gamma-ray sources have been discovered and are being monitored regardless of the day and the night. Hence, the Sun and Moon would have some impacts on the observation of gamma-ray sources, which have not been taken into account in previous analysis. In this paper, the influence of the Sun and Moon on the observation of very high energy gamma-ray sources when they are near the line of sight of the Sun or Moon is estimated. The tracks of all the known VHE sources are scanned and several VHE sources are found to be very close to the line of sight of the Sun or Moon during some period. The absorption of very high energy gamma rays by sunlight is estimated with detailed method and some useful conclusions are achieved. The main influence is the block of the Sun and Moon on gamma rays and the shadow on the cosmic ray background. The influence is investigated considering the detector angular resolution and some strategies on data analysis are proposed to avoid the underestimation of the gamma-ray emission.

Key words: astroparticle physics – Sun: general – methods: observational – Sun: UV radiation

1. Introduction

Very high energy (VHE, $E > 0.1$ TeV) gamma rays, located at the highest energy band of the cosmic electromagnetic radiation, are a powerful probe for astrophysics and fundamental physics under extreme conditions. Thanks to the advancements in ground-based gamma-ray detectors, our knowledge about the VHE gamma-ray universe has made impressive progress over the past two decades. The successful operation of the second generation Imaging Atmospheric Cherenkov Telescopes (IACTs), such as H.E.S.S. (Jung 2001), MAGIC (Baixeras 2003), and VERITAS (Weekes et al. 2002), has significantly increased the number of detected VHE gamma-ray sources from about 10 to over 200 since 2004. Due to the limitation of this technique which adopts optical detectors, the observation can only be implemented during a clear and moonless night. Therefore, the influence of the Sun and Moon and their light on the very high energy gamma-ray sources are ignored for a long time.

Recently, the sensitivity of another ground-based detector technique EAS arrays has greatly improved thanks to the successful operation of the new generation arrays, such as HAWC and LHAASO. The HAWC (DeYoung & HAWC Collaboration 2012; Springer 2016) and LHAASO (He & the LHAASO Collaboration 2018) observatories have detected 65 and 90 VHE sources (Albert et al. 2020; Cao et al. 2023), respectively. Since the EAS arrays adopt particle detectors, they have a large field of view which covers 1/7 of the whole sky at each moment, and they are usually operated with nearly full duty cycle regardless of the day and the night. In such a situation, some of the gamma-ray sources may be very close to the line of sight of the Sun or Moon during observation which would lead to the underestimation of the sources flux. Therefore, the influence of the Sun and the Moon on the very high energy gamma-ray sources near the line of sight should be carefully studied and a strategy is needed to guide the data analysis to avoid the underestimation of the gamma-ray emission.

When a gamma-ray source is very close to the line of sight of the Sun or the Moon, the measurement of the gamma-ray emission may be affected due to four factors. First, when a source is blocked by the Sun or the Moon, the gamma-rays from the source will not reach the Earth. Second, when a source is close to the line of sight of the Sun, the gamma-rays from the source will suffer the γ–γ absorption by the sunlight during their propagation to the Earth. The quantitative absorption should depend on the energy of the gamma rays and also depend on the space angle between the source and the Sun. The extinction of the VHE gamma-ray by sunlight has been noticed in a brief paper (Loeb 2022) when studying the TeV gamma-ray background, however, no detailed results are presented and the quantitative impact on gamma rays from a specific source is not estimated. Third, the Sun and Moon will produce a shadow

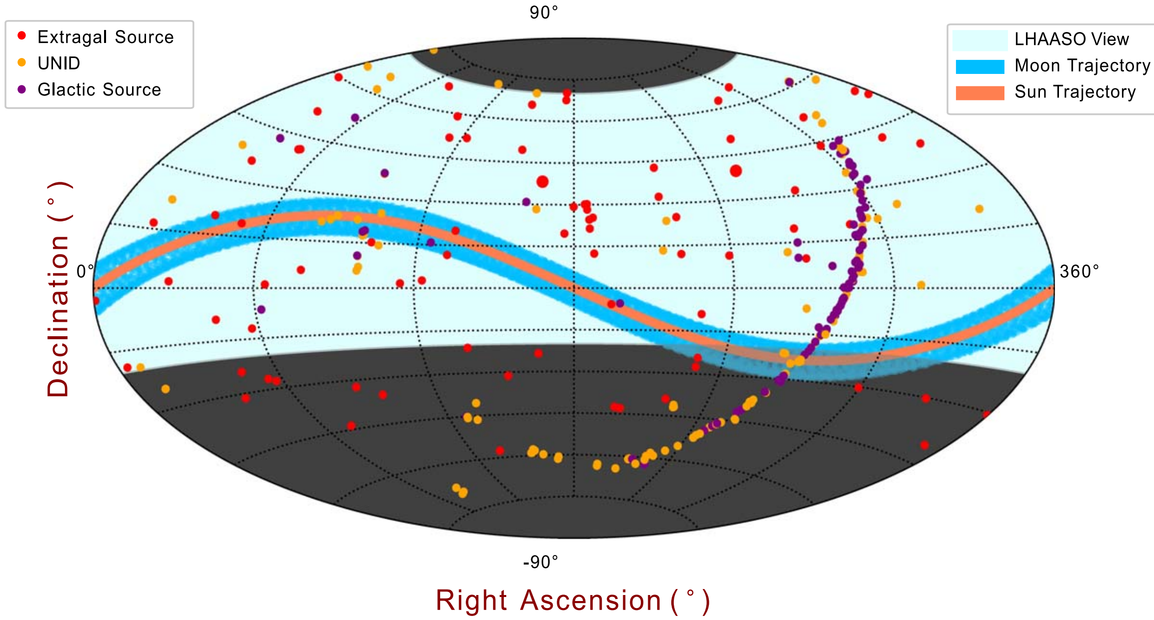

Figure 1. The track of Sun and Moon in the Equatorial Coordinates. The Points are TeV Sources listed in TeVCat, where the red points are Extragal Sources, the purple points are Galactic Sources, the orange points represent the UNID Sources. The light cyan region is the field of view of LHAASO. The orange line indicates the trajectory of Sun in one year. The sky blue belt is the trajectory of Moon in 18.6 yr.

on the cosmic ray background, which will lead to a deficit source that cancels the gamma-ray signals. These shadows have been well measured by EAS arrays with high significance and were adopted to calibrate detectors and perform physics measurements (Ambrosio et al. 1998, 2003; Aielli et al. 2011; Bartoli et al. 2011, 2017; Aartsen et al. 2021). Fourth, the Sun could also produce gamma-ray emission due to the interaction of cosmic rays with the solar atmosphere. The solar gamma rays have been well detected and studied using Fermi-LAT data at GeV band (Abdo et al. 2011; Ng et al. 2016; Linden et al. 2018; Tang et al. 2018). The emission at VHE band have been studied by several pieces of literature (Albert et al. 2018; Bartoli et al. 2019; Li et al. 2024) and a positive signal was also reported by HAWC collaboration recently (Albert et al. 2023).

In this paper, we will study the influence of the Sun and Moon on the very high energy gamma-ray sources near the line of sight. Especially the absorption of VHE gamma rays by sunlight will be quantitatively calculated for the first time. Then, we will explore some strategies on data analysis to avoid affection of the Sun and Moon on the measurement of the gamma-ray emission from the sources. The paper is organized as follows: the known VHE gamma-ray sources that may be very close to the Sun and Moon are explored in Section 2. The absorption of very high energy gamma ray by sunlight is calculated in Section 3 including method and results. Some strategies to avoid the effect of the Sun and Moon are presented in Section 4. Section 5 is the summary.

2. VHE Gamma-ray Sources that Could Be Close to the Line of Sight of the Sun and Moon

Due to the Earth's orbit around the Sun, the position of the Sun in the celestial coordinates varies annually. Figure 1 shows the track of the Sun in the celestial coordinates. The decl. of the Sun can vary from $-23.6°$ to $23.6°$. The track is about same every year. Due to the Moon's orbit around the Earth, the position of the Moon in the celestial coordinates varies with a duration of 29.53 days. Besides this monthly variation, the varying range of the decl. also varies with a duration of 18.61 yr. The maximum (minimum) decl. can change from $18.2°$ $(-18.2)°$ to 28.7 $(-28.7)°$. The track of the Moon in the celestial coordinates during the 18.61 yr is also shown in Figure 1. It is worth noting that both the Sun and Moon are extended sources in the sky with a radius about $0.26°$.

Up until now, about 300 VHE gamma-ray sources have been detected according to TeVCat.[4] All these sources are also presented in Figure 1. According to Figure 1, it is clear that some sources can be blocked by the Sun or Moon and some sources would be very close to the Sun or Moon during some period. Table 1 lists the 20 known VHE sources with a closest space angle of less than 2° from the Sun or Moon. The R.A. and decl. of the sources and their closest space angle to the Sun and Moon are presented in Table 1. These sources include both galactic and extra-galactic sources. Obviously, these sources

[4] http://tevcat.uchicago.edu/

Table 1
The VHE Sources with the Closest Space Angle Less Than 2° from the Sun or Moon

Source name	R.A. (°)	Decl. (°)	Closest Angle to Sun (°)	Closest Angle to Moon (°)
HAWC J0543+233	85.78	23.40	0.313	0.325
W 28	270.43	−23.33	0.315	0.375
3C 279	194.05	−5.79	0.513	0.428
HESS J1800-240B	270.11	−24.04	0.601	0.573
RBS 0413	49.95	18.76	0.603	0.410
HESS J1800-240A	270.49	−23.96	0.634	0.301
HESS J1800-240C	269.71	−24.05	0.709	0.436
IC 443	94.21	22.50	0.983	0.354
Crab Pulsar	83.63	22.01	1.307	0.558
Crab	83.63	22.01	1.308	0.560
Terzan 5	266.95	−24.81	1.413	0.563
HESS J1804-216	271.13	−21.70	1.735	0.426
SNR G004.8+6.2	263.35	−21.57	1.737	0.077
2HWC J1309-054	197.31	−5.49	1.765	0.278
Kepler's SNR	262.67	−21.49	1.790	0.478
VER J0521+211	80.44	21.21	1.928	0.241
1ES 0647+250	102.69	25.05	2.157	0.559
OJ 287	133.70	20.10	2.600	0.443
GRB 180720B	0.53	−2.94	2.911	0.442
HESS J1808-204	272.16	−20.43	2.997	0.265

should be treated carefully when measuring their gamma-ray emissions using the EAS array data. The impact of the Sun and the Moon will be studied later.

3. The Absorption of VHE Gamma Rays by Sunlight

It is known that that VHE gamma rays emitted from distant astronomical sources would be absorbed by low energy background photons through photon-photon interaction. This absorption leads to the opacity of the Universe to the VHE gamma rays. The absorption of gamma rays at a specific energy E is mainly due to the low energy photons with a wavelength around $\lambda \sim 1.5(E/1\ \mathrm{TeV})\ \mu$m. The gamma-ray opacity above 100 TeV is mainly due to the absorption *f* Cosmic Microwave Background (CMB) (Hauser & Dwek 2001). The gamma-ray opacity below 100 TeV is mainly due to the absorption of extra-galactic background light (EBL) in the intergalactic space (Finke et al. 2010; Saldana-Lopez et al. 2021). The interstellar radiation fields (ISRF) within our Galaxy would also absorb the gamma rays below 100 TeV with a visible fraction for some cases (Moskalenko et al. 2006). Before a cosmic VHE gamma-ray photon reaches the Earth, it should also pass through the sunlight. Therefore, the gamma ray should suffer the γ–γ absorption by the sunlight. The density of sunlight is dependent on the distance to the Sun r, which is in inverse proportion to $R_{\odot}^2$. The absorption should be dependent on the space angle between a gamma-ray source and the Sun. In the following, the Crab Nebula will be taken as an example to estimate the absorption by sunlight.

3.1. Estimation Method

To quantitatively estimate the absorption by sunlight, the radiation spectrum from the Sun is approximated as a blackbody spectrum with a temperature of 5800 K. The radiation power is in direct proportion to the surface area of the Sun. The luminosity at Earth is roughly consistent with the measurement achieved by American Society for Testing and Materials (ASTM) (ASTM International 2000), the E-490 solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance, and more detail can be found on the website,[5] as shown in the Figure 2. The peak luminosity is around 0.5 μm and the total emission power is 1366.1 W m^{-2} at the Earth. The density of sunlight photon $n_{\mathrm{pn}}(\nu, r)$ is dependent on the photon frequency ν and the distance to the Sun r, which can be written in the form of:

$$n_{\mathrm{ph}}(\nu, r) = \frac{2\pi\nu^2 R_{\odot}^2}{c^3 r^2} \frac{1}{e^{h\nu/KT} - 1} \tag{1}$$

where c is the speed of light, $R_{\odot} = 6.963 \times 10^{10}$ cm is the radius of the Sun, T is the temperature, K is the Boltzmann constant.

The cross section of the γ–γ absorption presented in (Dermer & Menon 2010) is adopted here:

$$\sigma_{\gamma\gamma}(s) = \frac{1}{2}\pi r_e^2 (1 - \beta_{\mathrm{cm}}^2)[(3 - \beta_{\mathrm{cm}}^4) ln \times \left(\frac{1 + \beta_{\mathrm{cm}}}{1 - \beta_{\mathrm{cm}}}\right) - 2\beta_{\mathrm{cm}}(2 - \beta_{\mathrm{cm}}^2)\Big] \tag{2}$$

[5] https://www.pveducation.org/pvcdrom/appendices/standard-solar-spectra

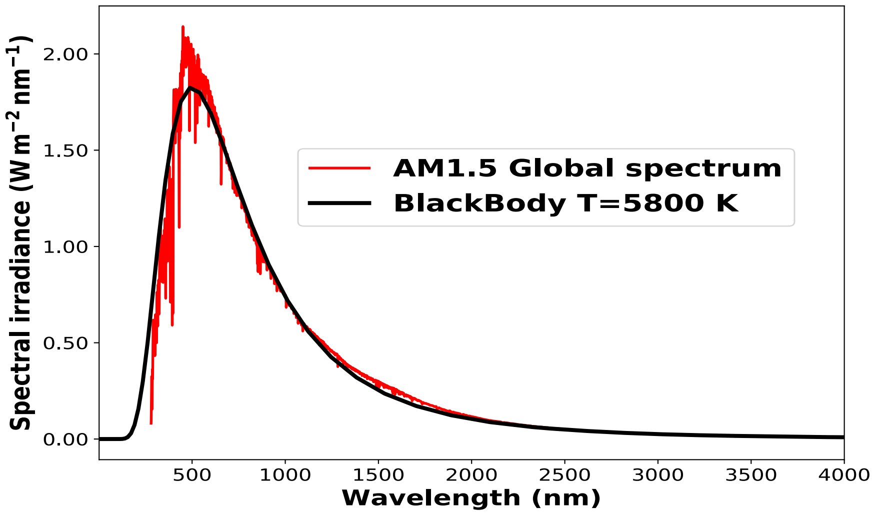

Figure 2. The luminosity of sunlight as the function of photon wavelength. The black line is the expected luminosity at Earth from a blackbody spectrum with a temperature of 5800 K at the surface of the Sun. The red line indicates the measurement achieved by American Society for Testing and Materials (ASTM).

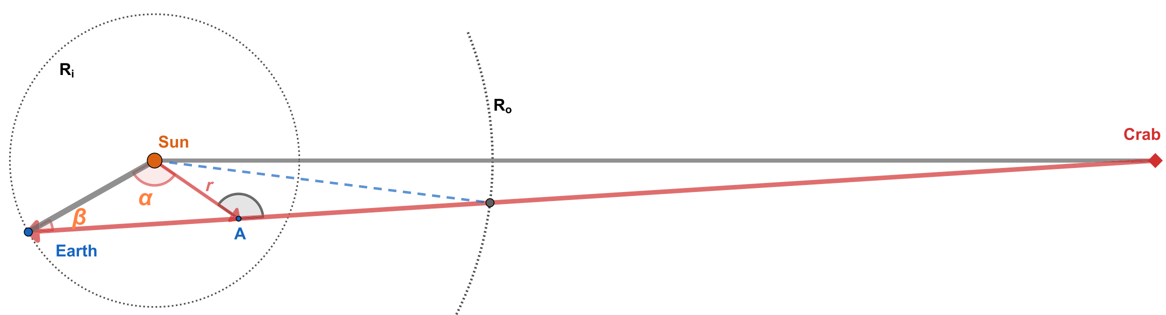

Figure 3. A schematic diagram shows the interaction between the gamma-rays from Crab Nebula with sunlight and the parameters used in the equations.

where r_e is the classical electron radius, $\beta_{\rm cm} = \sqrt{1 - s^{-1}}$, $s = \frac{1}{2}[E\epsilon(1 - \cos(\theta))]$ is the center-of-momentum frame Lorentz factor of the produced electron and position, E is the energy of the gamma ray, ϵ is the energy of the low energy photon, θ is the space angle between the direction of the low energy photon and that of the gamma ray.

With the density of the sunlight photon and the cross section of the γ–γ, the optical depth of the gamma ray from the Crab Nebula to the Earth due to the absorption of the sunlight can be estimated using the function:

$$\tau_{\gamma\gamma,SunLight} = \frac{1}{2}\int dx \int_{1/\epsilon}^{\infty} \times (1 - \cos(\theta)) n_{ph}(\epsilon, r) \sigma_{\gamma\gamma}(s) d\epsilon. \quad (3)$$

Here dx is integrated along the line from the Crab Nebula to the Earth as illustrated in the schematic diagram shown in Figure 3. In this figure, $R_o = 100$ au, and β is the space angle between the Sun and the Crab Nebula. In the calculation, we divide the integration interval into two segments, i.e., with r less than R_o and r larger than R_o. When $r < R_o$, the angle between the direction of the sunlight photon and the direction of the gamma ray changes rapidly. When $r > R_o$, the collision angle will be considered as consistent value $\phi = 180°$.

3.2. Estimation Result

Using Equation (3), we calculate the optical depth (τ) of gamma ray at different energies for different space angles between the Sun and the Crab Nebula. The survival fractions of the gamma ray $e^{-\tau}$ are shown in Figure 4. The absorption is clearly dependent on the gamma-ray energy and the space angle between the gamma ray and the Sun. According to Figure 4, the absorption of the gamma ray happens at a wide energy range from about 0.1 to 100 TeV with maximum absorption approximately at 0.89 TeV. When the space angle between Crab Nebula and Sun is 0.25°, which is at the boundary of the Sun, the maximum absorbed percentage is

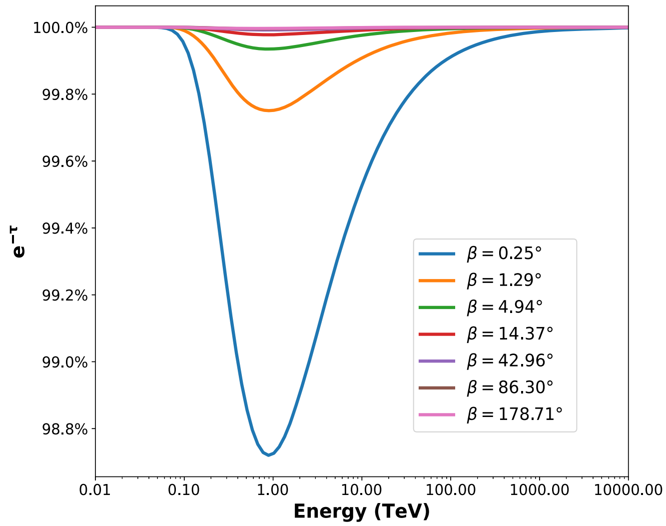

Figure 4. The survival fractions of the gamma-ray after the absorption of the sunlight. Different lines indicate the results using different space angle between the gamma-ray source and the Sun.

1.2%. It is worth noting that we have ignored the absorption due to the interaction between the gamma ray and the solar atmosphere, which should be heavy when the space angle is less than 0.°25. When the space angle is 1.29°, the maximum absorption ratio is 0.25%. The maximum absorption is less than 0.05% when the space angle is larger than 5°.

Due to the Earth's orbit around the Sun, the position of the Sun in the celestial coordinates varies annually. Hence the space angle between the Sun and Crab Nebula varies annually as shown in Figure 5, with maximum angle larger than 150° and minimum around 1.°29. We also estimate the absorption of the sunlight for gamma rays with different energies from the Crab Nebula as a function of the time as shown in Figure 5. Since the minimum space angle between Crab Nebula and Sun is 1.°29 occurred in the day of 3 July, the maximum absorption is less than 0.25%.

3.3. Cross Check About the Calculation Procedure

When gamma rays from the Crab Nebula travel toward the Earth, they are not only absorbed by low-energy sunlight photons, but also by cosmic microwave background (CMB) photons. The absorption process has been calculated in Cao et al. 2021. In order to validate the reliability of the calculation procedure presented in this paper, we have used the same computational procedures for sunlight photons to calculate the absorption of gamma-rays from the direction of the Crab Nebula by the CMB. In our calculations, the CMB radiation spectrum adopts a 2.7 K blackbody spectrum, and the CMB density is isotropic and position-independent, in contrast to the

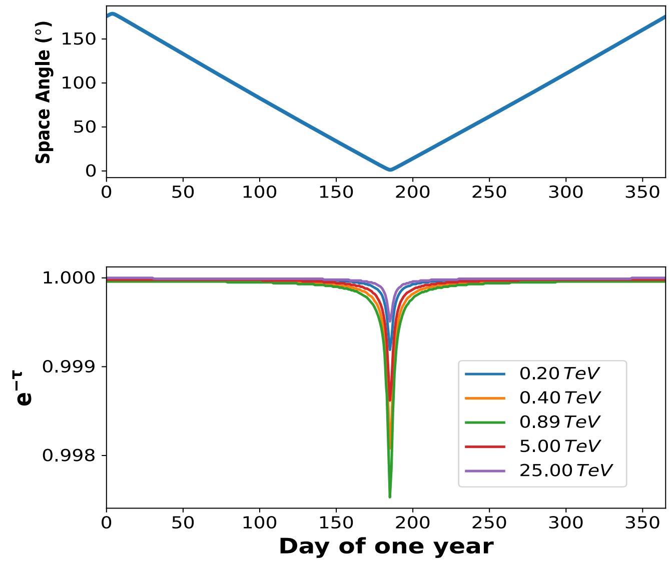

Figure 5. Upper: The space angle between the Sun and Crab Nebula as function of the time in one year. Lower: The absorption of the sunlight on gamma-rays with different energies, i.e., 0.2, 0.4, 0.89, 5, and 25 TeV, as function of the time in one year.

density of sunlight photons. The density of CMB is:

$$n_{\mathrm{ph},cmb}(\nu,\, t) = \frac{8\pi\nu^2}{c^3}\frac{1}{\exp\left(\frac{h\nu}{KT}\right) - 1}. \tag{4}$$

For the Crab, we do not need to consider the evolution of the Universe, the the optical depth of CMB is:

$$\tau_{\gamma\gamma,cmb} = \frac{1}{2}\int dx \int_{-1}^{1}(1-\mu)d\mu \int_{1/\epsilon}^{\infty} n_{\mathrm{cmb}}(\epsilon)\sigma_{\gamma\gamma}(s)d\epsilon \tag{5}$$

where $\mu = 1 - \cos(\theta)$. The total survival ratio of gamma rays as a function of energy is $e^{-\tau} = e^{-(\tau_{\mathrm{cmb}}+\tau)}$, as shown in Figure 6. The absorption of CMB on gamma rays is primarily observed at energies above 200 TeV, with the maximum absorption occurring at around 2 PeV, and an absorption probability of 25%. This result aligns with the findings in Cao et al. (2021), thus providing basic validation of the correctness of the calculations in this paper.

4. The Effect of the Sun and Moon on Gamma-ray Source Observation

Based on the calculations from the previous section, it is evident that the absorption of gamma rays by sunlight is extremely minimal and can be disregarded during most observation periods. The Moon primarily reflects sunlight and has a much lower brightness compared to the Sun, resulting in an even smaller absorption of gamma rays by moonlight, which can be directly ignored. However, when the angle between the direction of the gamma-ray source and the directions of the Sun

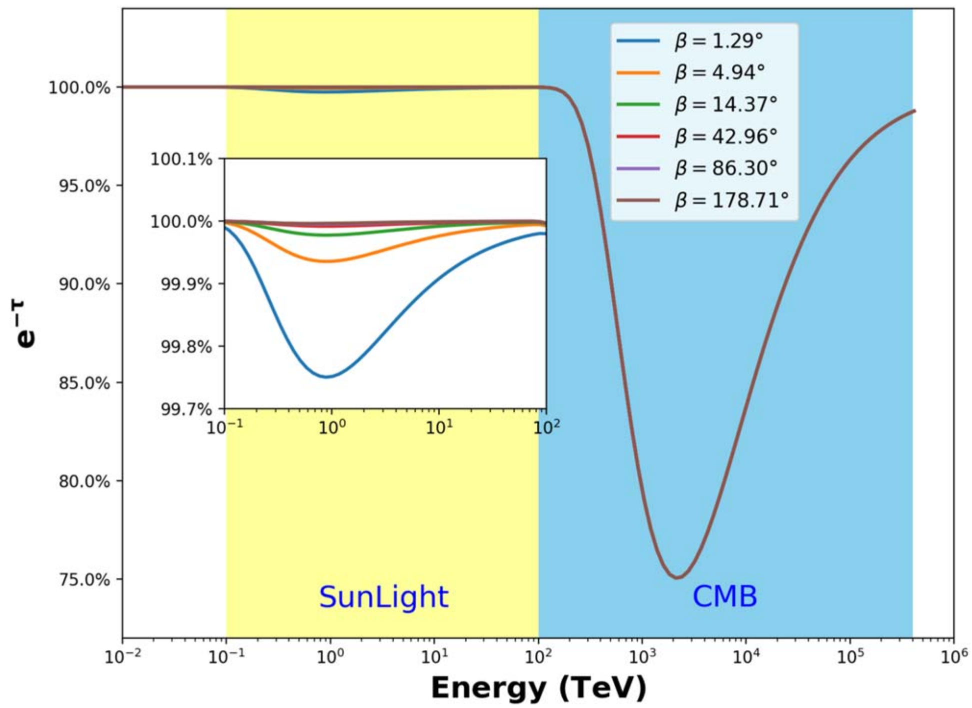

Figure 6. The survival fractions the gamma-ray after the absorption by the sunlight and the CMB photons. Different lines indicate the results using different space angle between the gamma-ray source and the Sun.The yellow region represents the absorption of sunlight, while the sky blue region mainly corresponds to the absorption of CMB.

and Moon is less than 0°.25, the gamma rays will be completely blocked by the Sun and Moon, and cannot be ignored during this time period. Therefore, it is necessary to exclude this data during the analysis.

Additionally, when the angle between the direction of the gamma-ray source and the directions of the Sun and Moon is small, the Sun and Moon directly block the cosmic ray background, creating a missing negative source. This shadow can counteract the gamma-ray signal, and its impact depends on the ratio of the number of gamma-ray signals to the background. For previous arrays like ARGO-YBJ, which lacked the ability to distinguish between gamma ray and cosmic ray background, the gamma-ray signals only accounted for a small portion of the backgrounds. For example, in observations of the brightest gamma-ray source, the Crab Nebula, the gamma-ray signals were only about 1% of the backgrounds (Bartoli et al. 2015), leading to a significant counteracting effect from the shadow on the gamma-ray signals.

For the LHAASO array, due to its excellent ability to distinguish between gamma rays and cosmic ray backgrounds, the proportion of gamma rays to backgrounds has significantly increased. For example, in observations of the Crab Nebula, the ratio of gamma-ray signals to backgrounds for the LHAASO-WCDA array is 20% at 1 TeV, 80% at 6 TeV (Aharonian et al. 2021a), and for the LHAASO-KM2A array, the corresponding ratios are 12% at 10 TeV, 260% at 25 TeV, and 4100% at 100 TeV (Aharonian et al. 2021b). However, considering the current detection sensitivity of LHAASO is at 1% of the Crab flux level, the impact at energies below 100 TeV cannot be ignored.

Figure 7 shows the counteracting effect of the Sun or the Moon's shadow on the gamma-ray signals at different space angles. In this example, we assume the detector angular resolution to be 0°.5 and the number of deficit shadow events to be three times that of the gamma-ray signals. This situation is similar to the observation of LHAASO-KM2A on a gamma-ray source with a flux around 10% Crab unit at 10 TeV. It is clear that the gamma-ray signals will be completely counteracted by the shadow when they are very close the direction of the Sun or the Moon. The counteracting effect decreases with the increase of the space angle. To ensure safety, we recommend removing data when the space angle between the gamma-ray source and the direction of the Sun and Moon is less than 3 times the angular resolution plus 0°.25. For example, the observation time of the EAS array for the Crab is approximately 7 hr per day, and only during a few days the space angle between the Crab and Sun or Moon is less than 2° in one year. The data from this period of observation can be excluded for data analysis, thus eliminating its impact. Since the angle between the source and the directions of the Sun and Moon varies

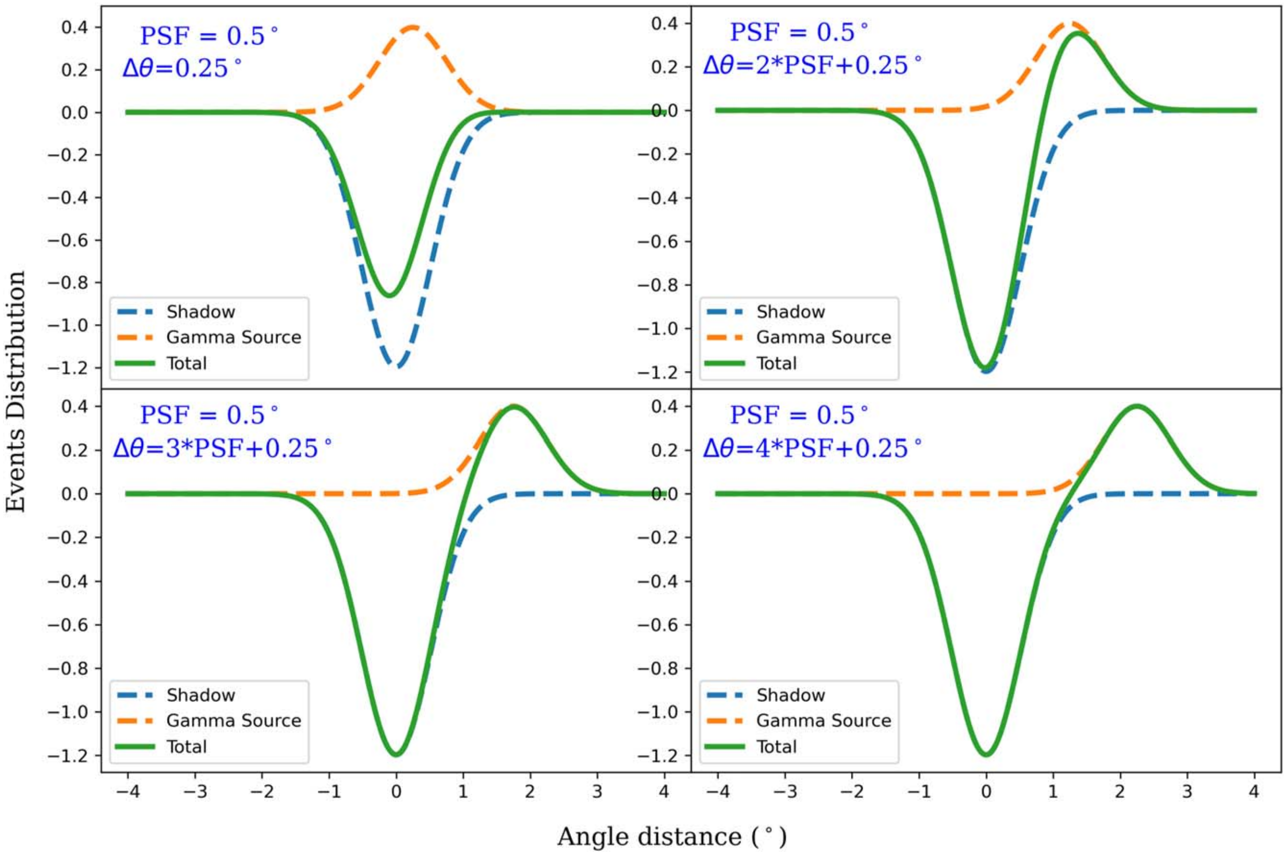

Figure 7. The impact of the shadow caused by the Sun or Moon on the observation of gamma-ray sources at different space angles, i.e., 0°.25, 2*PSF+0°.25, 3*PSF +0°.25, and 4*PSF+0°.25. The detector angular resolution (denoted as PSF) is assumed to be 0°.5. The number of deficit shadow events is assumed to be three times that of the gamma-ray signals from the source.

periodically, this portion of the data accounts for a very small percentage, generally less than 1% of the total observation time in one year, and therefore does not significantly affect the observation of the source.

When measuring their radiation using EAS arrays such as LHAASO and HAWC, special attention should be paid to excluding data when the space angle between the source and the Sun or Moon is small.

5. Summary

With significant advancements in ground-based extensive air shower arrays, numerous VHE gamma-ray sources have been discovered and are being continuously monitored by LHAASO and HAWC, regardless of day or night. With investigating the celestial coordinates of the Sun and Moon, we identified 20 sources that can come close to the line of sight of the Sun or Moon during certain periods. We have conducted the first estimation of sunlight absorption on VHE gamma rays. The absorption primarily affects gamma rays with energies ranging from 0.1 to 100 TeV, with maximum absorption occurring around 0.9 TeV. The absorption is contingent on the spatial angle between the Sun and the sources; however, the overall absorption is minimal, with a maximum of less than 1.2%. The primary influence is the obstruction of the Sun and Moon on gamma rays, and their shadow on the cosmic ray background. The impact is also contingent on the detector's angular resolution. To mitigate its effects, we recommend excluding data when the angle between the gamma-ray source and the directions of the Sun and Moon is less than a certain value taking into account the experiment angular resolution.

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