



Probing the CR positron/electron ratio at few hundreds GeV through Moon shadow observation with the MAGIC telescopes

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Abstract: The antimatter components measured in the Cosmic Ray (CR) flux are thought as secondary particles induced by the propagation of galactic CRs within the galaxy. Recent results from the PAMELA experiment show an unexpected increase of the positron electron ratio above 10 GeV. There could be different interpretations to explain that result, the most discussed ones being the signature of nearby compact astrophysical source(s) or of dark matter annihilation/decay. Probing the positron-fraction rise above 100 GeV would help to disentangle among different scenarios. Imaging Atmospheric Cherenkov Telescopes (IACT) can extract the cosmic lepton signal from the hadronic CR background between a few hundred GeV and a few TeV and reconstruct energy and incident direction with a very good resolution. In addition, by using the natural spectrometer formed by the Moon and the geomagnetic field, it is possible to measure the positron/electron ratio at the TeV regime through the observation of the CR Moon shadow. Despite the technique is particularly challenging because of the high background light induced by the Moon and the treatment of data, the MAGIC collaboration has performed for the first time such observations in 2010 and 2011. Here we present the observation strategy and the performance achieved during this campaign.

Keywords: Cosmic ray, electron, positron, Moon shadow, MAGIC

1 Introduction

The propagation of cosmic rays (CRs) in the galaxy induces secondary particles by interaction with the interstellar medium. The relative abundance of different CR components (\bar{p}/p , B/C), as well as the diffuse γ -ray emission at the GeV regime, strongly constrain the CR propagation models [1]. Generally, these models predict a smooth all-electron ($e^+ + e^-$) spectrum decreasing faster than a power law E^{-3} above a few tens of GeV and a positron fraction $e^+/(e^+ + e^-)$ decreasing slowly with the energy. However, recent measurements show a different picture (see Fig 1). The all-electron spectrum measured with *Fermi*-LAT [2], ATIC [3], H.E.S.S. [4] and MAGIC [5] is harder than expected above 30 GeV with a break around 800 GeV. In the ATIC data the feature is even more pronounced with a significant bump around 500 GeV. Furthermore, PAMELA [6, 7] reported an increasing positron fraction above 10 GeV, in agreement with the previous results of HEAT [8] and AMS-01 [9], and recently confirmed by *Fermi*-LAT [10].

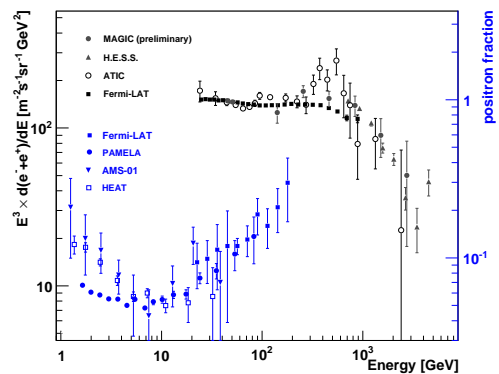


Figure 1: CR ($e^+ + e^-$) spectrum [2, 3, 4, 5] and the positron fraction ($e^+/(e^+ + e^-)$) [6, 8, 9, 10].

The anomalies in the e^+ and e^- fluxes are generally interpreted as the presence of a new component with a harder spectrum and a higher e^+/e^- ratio than the fluxes expected by classical CR models. Because of the short lifetime of

TeV electrons in the galaxy, this extra-component must come from nearby sources ($< 1 - 2$ kpc). Many scenarios involving dark matter (annihilation/decay), pulsars or modified CR propagation models have been proposed to interpret the data [11]. The positron fraction predicted by these models above 100 GeV can be very different. Measurement of this ratio at higher energies is thus essential to discriminate between models and to establish a connection between the e^+ fraction rise and the all-electron bump.

In the near future, PAMELA, AMS-02 [12] or *Fermi*-LAT may extend at higher energy their e^+ fraction measurement by collecting more data but more likely they should not reach much higher energies than 300 GeV. Using the Moon shadow effect, Imaging Atmospheric Cherenkov Telescope (IACT) experiments could measure or constrain the e^+/e^- ratio around 1 TeV. The idea of probing the e^+ fraction by the observation of the Moon shadow has been proposed at the last ICRC [13]. Since then, the MAGIC collaboration has developed this new detection technique and collected several hours of data in stereoscopic mode. In the next section, the principle of the Moon shadow effect is explained. Then, in section 3, the Moon shadow observation strategy with MAGIC and the data analysis method are presented. Finally, the performance of such method estimated from MC simulation on Crab Nebula data taken in similar experimental conditions (high Moon light level), is discussed in section 5, followed by concluding remarks.

2 The Earth/Moon spectrometer

The Earth/Moon system forms a natural spectrometer in which the Moon absorbs a part of the CRs creating a “hole” in the isotropic flux (so called the Moon shadow) and the Earth magnetosphere deflects the trajectory of any coming particle depending on its charge and momentum (equivalent to its energy for an ultra-relativist particle). Then, the position of the Moon shadow in the sky (observed from ground) is different for each CR. For neutral CRs (like diffuse γ rays), it lies at the actual Moon position. For charged CRs, the Moon shadow is shifted perpendicularly to the geomagnetic field along an axis close to an East-West orientation. Negative and positive CRs are shifted respectively eastward and westward. The amplitude of the deviation depends on the particle rigidity. For ultra relativistic particles, it is simply proportional to its charge Z and inversely proportional to its energy E . The typical deviation for medium zenith angle observation ($\sim 45^\circ$) is about $1.5^\circ \times Z \times 1 \text{ TeV}/E$.

The Moon shadow effect is used by ground-based EAS detectors and cosmic neutrino experiments to estimate their angular resolution and pointing accuracy [14, 15, 16]. As most of the CRs are positive particles (atom nuclei), the all-CR Moon shadow is asymmetric with a larger deficit at the west side of the Moon. EAS experiments with the lowest energy threshold have detected this East-West asymmetry and derived upper limits on the \bar{p}/p ratio ($\sim 5 - 10\%$) at the TeV regime [17, 18, 14]. However the poor electron/proton

discrimination of these experiments do not allow them to extract the electron signal from the hadron CR background. In contrast, IACT experiments are able to distinguish electromagnetic showers (induced by γ rays and electrons) and hadronic showers with a very good accuracy. H.E.S.S.[4] and MAGIC [5] measured the all-electron spectrum from 100 GeV to a few TeV. Therefore, in principle, they could also probe the e^+/e^- ratio in this energy range using the Moon shadow effect. However, the Moon shadow lies only a few degrees from the Moon and then the dazzling background light induced by the scattered moonlight must be handled properly. The first try to observe the Moon-shadow effect with IACT was performed in the 90’s with the ARTEMIS experiment [19], which was using UV-filter (200 – 300 nm) to suppress most of the moonlight. Unfortunately, the Cherenkov light of the air showers was strongly suppressed too, and the Moon shadow could not be detected.

Here, with MAGIC, we are using a different approach which do not include major hardware modifications. All the coming photons are recorded and then the background light is excluded during the image cleaning stage.

3 Observation with MAGIC

MAGIC is a pair of 17 m IACT located at the Canary Island of La Palma, 2200 m above sea level, built for very high energy γ -ray astronomy. The stereoscopic system has been in operation since fall 2009. It generally operate during dark nights when it reaches its lower energy threshold (~ 50 GeV) and a sensitivity above ~ 300 GeV of 0.8% of the Crab Nebula in 50 h [20]. The MAGIC camera uses low gain PMTs with only 6 dynodes, covering 3.5° field of view, that can be operated at high background light levels without any damage. MAGIC observes astrophysical objects under moderate moonlight for long time. The sensitivity above 200 GeV is almost unaffected by an increase of the Night Sky Background (NSB) 5 times higher than a dark-night sky [21].

The Moon shadow observation with MAGIC is performed on the energy range 300 – 700 GeV, where an excess in the all-electron spectrum is measured, and where the e^+ fraction is unknown (see figure 1). The position of the electron Moon shadow at such energies ranges lies between 2° and 6° from the Moon. Thus we point the MAGIC telescopes at about 4° from the Moon. As the Moon shadow spreads out in only one direction (East-West) it can be contained in one half of the camera. The other half is then used for the background estimation. Figure 2 shows the typical observation of the Moon shadow with the MAGIC telescopes. The camera center tracks a point 0.6° away from the targeted electron shadow position (400 – 500 GeV) in a direction perpendicular to the Moon shadow deviation axis. The telescopes point alternatively (every 10 min) at each side of the Moon shadow axis for a better control of the systematics (wobble observation).

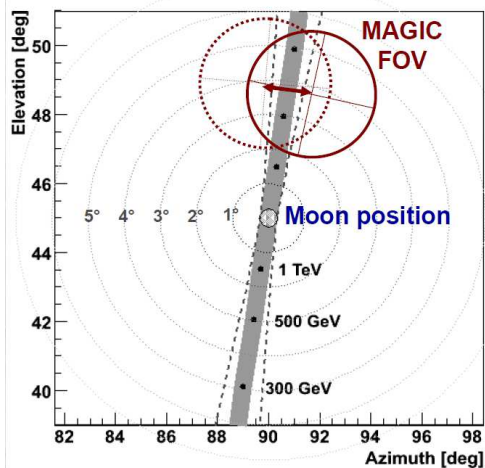


Figure 2: Positions of the Moon shadows for an observer at the MAGIC site with a rising Moon at 45° of elevation. The e^- shadow is below the Moon (Eastward) and the e^+ shadow above the Moon (Westward). The dashed lines represent the position uncertainty induced by a 10% error on the geomagnetic field. The light-gray dotted circles are the curves of iso-distance to the Moon. The red circles show the MAGIC field of view during e^+ shadow observation (wobble mode) of the energy range 300 – 700 GeV.

In order to track automatically the correct position, the drive system was modified to use a table providing the angle and amplitude of the Moon shadow deviation as a function of the azimuth and zenith angle of the observation. For the 2010–2011 observations, the table was built using a simple dipole model for the geomagnetic field. The real position of the Moon shadow can be then slightly off-centred ($< 0.3^\circ$) but this can be corrected afterward during the data analysis using a more precise model.

In order to preserve the quality of the PMTs, lower high voltages than standard values are applied. The PMT gain is reduced by a factor of ~ 1.5 . Then, the telescopes can be operated with a NSB light ~ 40 times higher than moonless-night extragalactic NSB. With this relatively low gain reduction, the standard PMT calibration method can be used. The NSB induced by squattered moonlight increases dramatically with the Moon phase and with the proximity to the Moon. At 4° from the Moon, the MAGIC telescopes can operate safely below 50% Moon phase.

The fast MAGIC data-acquisition system (2 GSamples/s) associated with small pixel sizes (0.1°) allows a highly performing image cleaning method [22]. Tight time constraints (of the order of 1 ns) between neighbour pixels are required. The cleaning levels were increased until fake signals appear in less than 10% of events. The obtained cleaning levels are about twice as high as the standard ones used for dark night observations.

The energy threshold achieved after the image cleaning is about 200 GeV at 30° from zenith. Figure 3 shows the energy threshold for electrons as a function of the zenith

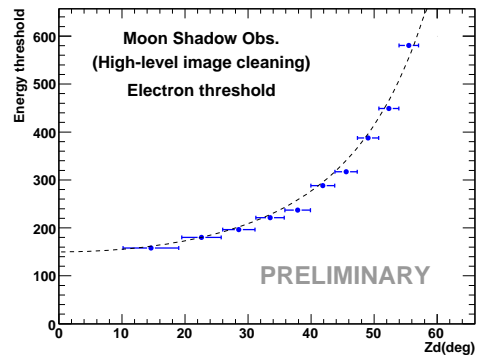


Figure 3: MAGIC energy threshold for electrons during the Moon shadow observation as a function of the zenith angle

angle. Beyond 50° from zenith, the energy threshold is well above 300 GeV and increases dramatically. Thus, we restrained the observation to zenith angle below 50° . As a small phase corresponds to a small angle between the Moon and Sun, a small-phase Moon is rarely close to zenith during the night. There are only about 40 h/year with a $< 50\%$ -phase Moon at less than 50° from zenith during the night. When this happens, the Moon is towards the East (rising just before the Sun) or towards the West (falling just after the Sun set). As it is shown Figure 2, in this configuration the Moon shadow spreads almost vertically above and below the Moon. The shadow above the moon is in a better position to be observed because closer to zenith (lower energy threshold) and further away from the bright side of the Moon (less background light). Then, we observe the e^- shadow at the beginning of the nights from December to May and the e^+ shadow at the end of the nights from August to January.

4 Performance and prospect

In order to check the performance of the MAGIC telescopes, we observed the Crab Nebula (standard candle of γ -ray astronomy) in the same conditions as the Moon shadow. We carried out 2.1 h of observation at zenith angle from 8° to 40° . Data are analyzed with the same method as the Moon shadow data (same image cleaning). Figure 4 shows the θ^2 plot¹ obtained with these data above 300 GeV. It corresponds to a sensitivity in 50 h of about 1.2% of the Crab Nebula flux. The angular resolution is almost not degraded by the high NSB level ($< 0.1^\circ$). It is anyhow much smaller than the Moon radius ($\sim 0.25^\circ$).

The shape of the Moon shadow as seen by MAGIC does not depend only on the angular resolution but also on the energy resolution because the assumed deviation angle depends on the estimated energy. From simulation, we estimated the energy resolution to be below 20% for diffuse electrons. We expect a deficit extension of about the

1. θ is the distance between the reconstructed event direction and the source position

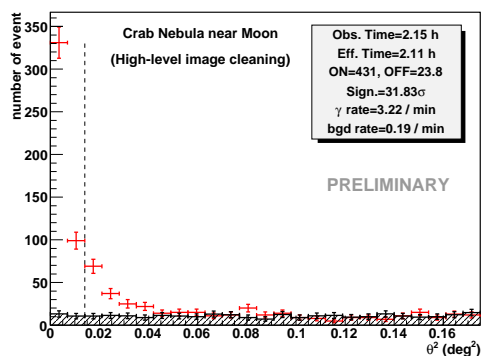


Figure 4: θ^2 distribution (>300 GeV) for the Crab Nebula observed with the same NSB light as Moon shadow observation.

Moon size in the direction perpendicular to the deviation axis (North-South) and 2–3 times larger along the deviation axis (East-West). For such extended sources, the sensitivity of MAGIC is reduced by a factor 2–3. Moreover, only the electrons with energy inside the target range (300-700 GeV) must be counted. Eventually, a preliminary estimation of the sensitivity of MAGIC for the Moon shadow is about 4.4% Crab Unit.

The total missing flux of the electron-positron Moon shadow is the product of the all-electron spectrum (figure 1) and the solid angle of the Moon $(6.6 \pm 0.8) \times 10^{-5}$ sr which varies of $\pm 12\%$ as a function of the observer-Moon distance. This missing flux is shared between the e^- and the e^+ shadows. Table 1 gives the mean missing flux between 300 and 700 GeV in Crab unit for the e^- and the e^+ shadows according to several hypothesis. It shows also the estimated MAGIC observation time required for a detection. In realistic scenarios, MAGIC would need about 50 h to detect the e^- shadow and at least 100 h for the e^+ shadow. This is longer than the available time per year (~ 20 h for each shadow). Because of bad weather, we collected in fact < 10 h per shadow during 2010-2011 campaign. With the current observation strategy, MAGIC would need then several years for a significant detection.

Composition hypothesis	Missing flux 300-700 GeV	Detection time with MAGIC
MAGIC spectrum [5]:		
100% e^-	5.4%	~ 30 h
80% e^-	4.3%	~ 50 h
60% e^-	3.3%	~ 90 h
40% e^+	2.2%	~ 200 h
20% e^+	1.1%	~ 800 h
ATIC spectrum [3] :		
100% e^-	7.2%	~ 20 h
80% e^-	5.7%	~ 30 h
60% e^-	4.3%	~ 50 h
40% e^+	2.9%	~ 100 h
20% e^+	1.5%	~ 400 h

Table 1: Mean missing flux of the Moon shadow in Crab nebula γ -ray-flux unit for different composition hypothesis.

The next generation of IACT (CTA[23]) should have a sensitivity an order of magnitude better than MAGIC. If observation with strong Moon light is possible, the e^- shadow detection time would decrease dramatically (< 5 h). The accessible energy range should also widen at lower energies thanks to larger telescopes with larger field of views, and at higher energies thanks to larger effective collection area.

5 Conclusion

Using the Moon shadow effect, IACT arrays have a chance to measure cosmic ray e^+/e^- ratio at energies hardly accessible with satellite experiments. Probing this ratio at the TeV regime is particularly interesting because of features were reported in the all-electron spectrum and because the positron fraction shows an unpredicted rise above 10 GeV. However observation near the Moon is very challenging for IACT because of the high NSB induced by the scattered moonlight. Using low gain PMT with reduced HV, the MAGIC collaboration started observation of the electron Moon shadow in the energy range 300-700 GeV. These observations carried out at 4° from the Moon provide an energy threshold of 200 GeV and a sensitivity above 300 GeV corresponding to 1.2% Crab Nebula units. In spite of this good performance, the detection of the electron Moon shadow with MAGIC will require several years because of the short observation window available every year.

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