

The Galactic Center region imaged with MAGIC and variability searches during the G2 pericenter passage

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The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes have observed the Galactic Center during the past four years. Due to its location in the northern hemisphere, MAGIC observes the GC at large zenith angles (58-70 deg), resulting in a higher energy threshold, but an enhanced effective collection area at multi-TeV energies.

The primary goal of this campaign was searching for variability in the very high energy gamma ray regime during the closest approach of the G2 gas cloud, which orbits the GC on a highly eccentric trajectory with a pericentre distance of only a few thousand Schwarzschild radii. These observations, apart from searching for variability, allowed us to perform morphological and spectral studies of the region, based on a large data set of about 80h.

No variability was detected in the 2013 and the 2014 data set. The diffuse TeV emission around GC could be imaged with great sensitivity, which led to the detection of TeV gamma rays from a region 0.2 deg away from SgrA* that is spatially coincident to the extended radio structure called Arc.

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1. Introduction

1.1 The Galactic Center Region

The central region of our galaxy is very densely populated with a large variety of astrophysical objects, many of which may be sites of extreme particle acceleration and hence gamma-ray emission. The most particular candidate for such an accelerator is the super massive black hole (SMBH), which is identified with the point-like radio source SgrA* and known to be the dynamical center of stellar motion in the central region of our galaxy [1, 2, 3, 4].

The Galactic center (GC) has also been extensively observed in the high energy (HE; $\gtrsim 100$ MeV) regime with the EGRET and *Fermi*-LAT instruments and in the very high energy (VHE, $\gtrsim 100$ GeV) regime with Imaging Atmospheric Cherenkov Telescopes [5, 6, 7, 8, 9]. More recent observations have shown that part of the TeV emission comes from a point-like object that coincides with the location of SgrA* within angular resolution and revealed that the area hosts an extended emission region, the GC ridge [10, 11, 12].

1.2 The periastron passage of the G2 Gas Cloud

The G2 gas cloud was discovered in VLT data and found to be on a highly eccentric orbit towards the central black hole (BH) of our galaxy [13]. This object with an estimated mass of about three times the Earth's was predicted to experience its periastron passage around mid 2013 at a distance of about 2200 Schwarzschild radii [14].

It is still subject to discussion, whether G2 is actually a gas cloud or rather a star or a star with stellar wind [15, 16]. Predictions vary from no effect at all to strong flaring activity of SgrA* [17, 18]. Some suggest that G2 may interact with stellar mass black holes that are expected to exist in the vicinity of SgrA* [19].

Regardless of the poor knowledge of the exact properties of G2, given the rarity of such an event, instruments in many wavebands started monitoring campaigns of SgrA*. So far no detections of abnormal activity have been reported [20, 21, 22]. There is however a hint for increased flaring activity in X-ray during 2013/14 [23].

1.3 The MAGIC Telescopes

The MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescopes are two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACT). They are located at a height of 2200 m a.s.l. in the Roque de los Muchachos Observatory on the Canary Island of La Palma, Spain (28°N, 18°W). The telescopes are used for observations of Cherenkov light flashes produced by superluminal charged particles in Extensive Air Showers (EAS) initiated by gamma-ray photons with energies $\gtrsim 50$ GeV.

Both telescopes are nominally operated together in the so-called stereoscopic mode, in which only events seen simultaneously in both telescopes are triggered and analyzed [24]. At energies around a few hundred GeV, for low Zenith distance (Zd) observations, the energy resolution is approximately 16% with a systematic bias on the order of 15% [25], while the angular resolution of the system is $\lesssim 0.07^\circ$. The sensitivity above 220 GeV is $(0.66 \pm 0.03)\%$ Crab Units (CU) for 50 hours of observations at low zenith angles.

1.4 The MAGIC GC Observation Campaign

The GC region observing campaign began in April 2012, and was intended as a long-term monitoring program spanning over several years. Since then around 80 hours of good quality data have been recorded.

When observed from the MAGIC site, the GC culminates at 57.78° Zd. This has strong implications for the observation conditions and the available time slots for observations. When observing at such large inclination (58° - 70°) the Cherenkov light pool at ground level produced by EAS is increased by a factor 4 to 10 in area. This implies a higher energy threshold, but also leads to an increased collection area by around this factor. Such observations with the MAGIC telescopes provide excellent sensitivity for energies $\gtrsim 1$ TeV. The time window for observing the GC with MAGIC when setting the Zd limit to 70° is approximately from mid-February until the end of September.

2. Data Analysis and Results

2.1 Data selection

Given that the GC was observed at such large Zd, the impact of the atmosphere on the data quality is increased compared to low Zd observations. This accounts for the effect of decreased transmission, as well as the increase of scattered light from the moon or terrestrial sources. The measurement of flux above a certain energy threshold is most sensitive to changes of atmospheric transmission. Therefore two different data quality selection classes were introduced: one for spectral and morphological studies and one with even stricter selection criteria for producing the light curve.

2.2 Data Analysis

After applying quality cuts the data could be analyzed with the standard MAGIC software tools starting from single telescope image parameter files, that are then combined through the calculation of stereo parameters.

Random Forests (RFs) based on simulated gamma rays are used for event classification, direction reconstruction and gamma-hadron separation. All events classified as gamma rays are used for the extraction of signal and background from suitable regions. SgrA* was observed in the so-called Wobble mode, where the source is observed in symmetric positions in the camera plane, all with an offset of 0.4° from the camera center. For the production of the spectrum and light curve, symmetric regions that are located off the Galactic plane were used for the background estimation. For the production of sky maps the blind map method was used, which compares the camera positions exposed to different regions of the sky for finding the best background estimate for the given camera position.

2.3 Variability Search

For the production of the light curve only data that fulfilled selection criteria for very clear skies was used, which is currently available only for the 2013 and 2014 data. The total amount of data in this sample corresponds to an observation time of about 45h. The flux from a region of

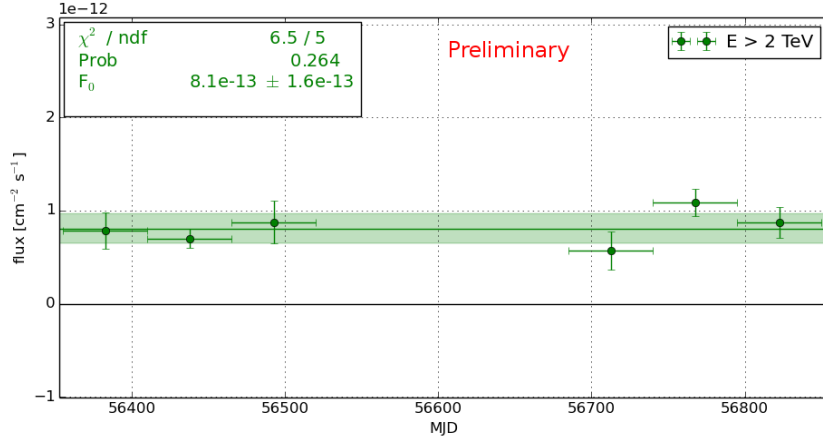


Figure 1: Light curve of integral flux F above 2 TeV from 0.14° radius around SgrA* with 50d binning for 2013 and 2014 data

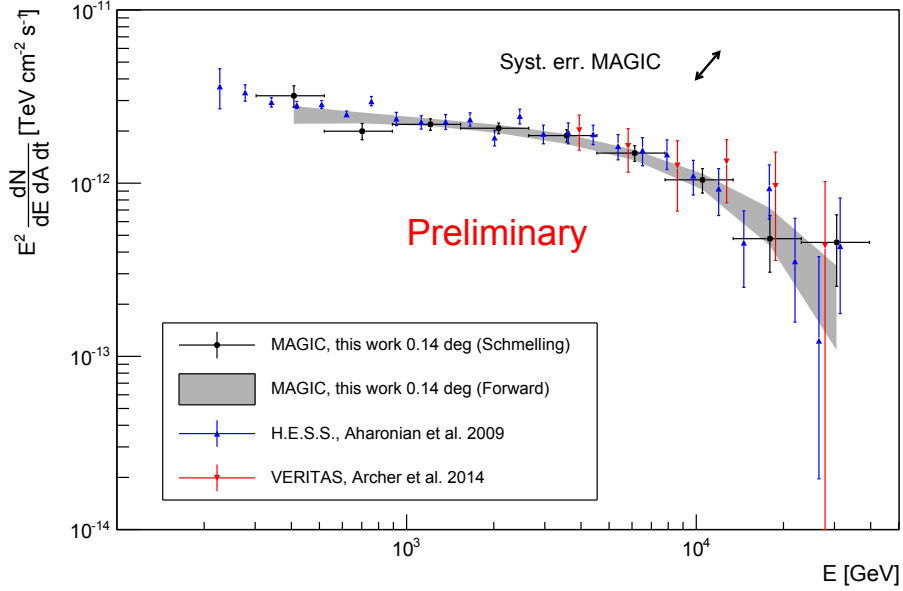


Figure 2: SED of the GC point-source extracted from a 0.14° radius region around SgrA*, compared to previous measurements by H.E.S.S. and VERITAS. MAGIC data is shown as unfolded spectrum (data points) and power-law function with cut-off from forward folding (shaded region).

radius 0.14° around the location of SgrA* (RA 266.4168° , Dec -29.0078°) was measured in time bins of 50d length. Figure 1 shows the light curve of the integral flux F above 2 TeV for 2013 and 2014 data. No significant deviation from a constant flux has been found.

2.4 Spectrum of the SgrA* point source

The same extraction region that was used for the light curve was also used for the SED, but using the data set with slightly relaxed data selection criteria and for the years 2012, 2013, 2014 and 2015 (in total ~ 80 h). Figure 2 shows the SED obtained from the new observations by MAGIC compared to previous measurements by H.E.S.S. and VERITAS [10, 12]. The best fitting param-

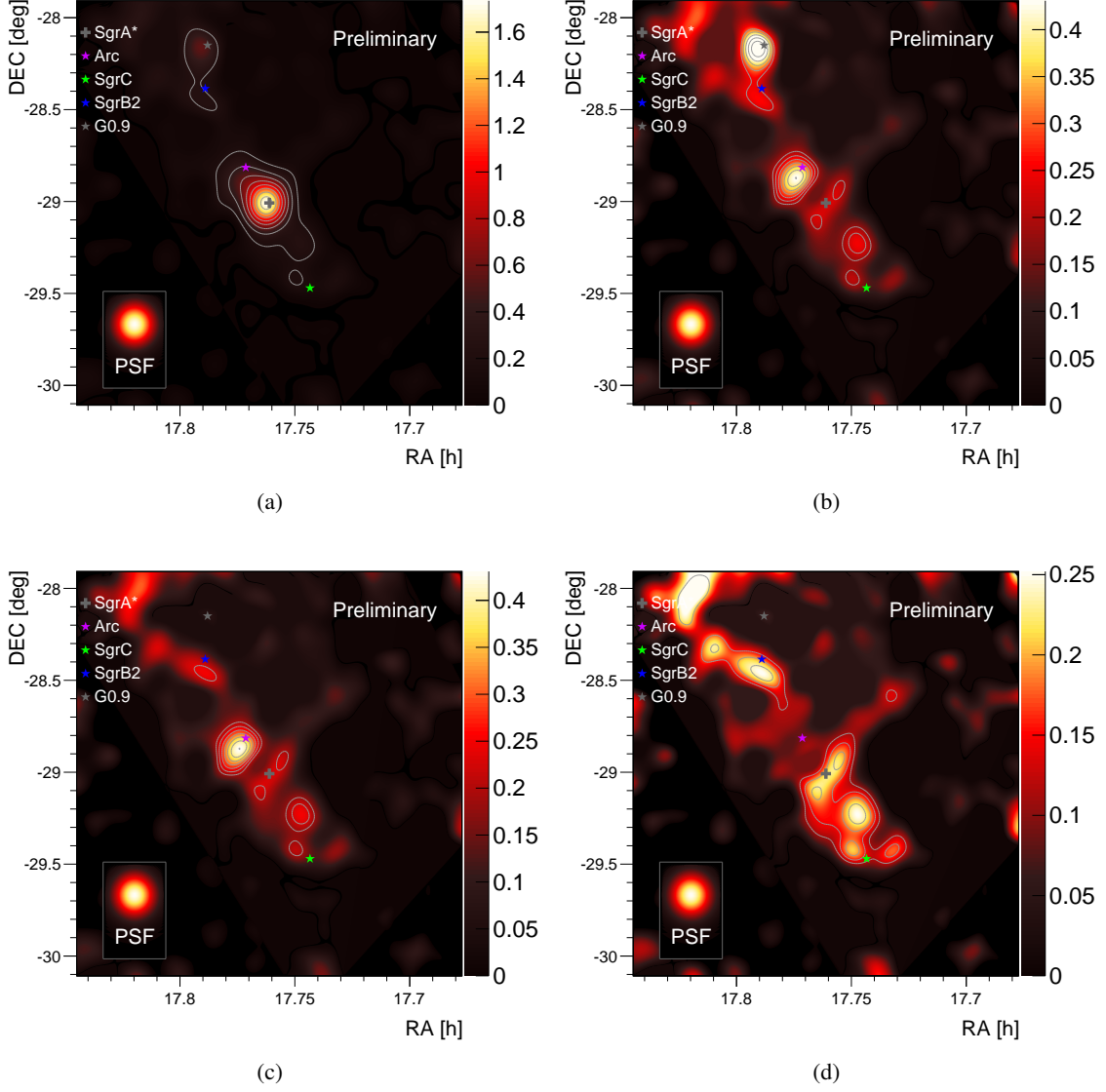


Figure 3: Sky maps based on 80h data set for energy range of $E \gtrsim 1$ TeV: relative flux map with significance contours starting from a minimum of 5σ local significance (a), residual map after subtracting the fitted SgrA* point source (b), after subtracting G0.9+0.1 in addition (c), residual map after subtracting also the emission region close to the arc with significance contours starting at 3σ (d).

ters when assuming a power-law function with exponential cut-off

$$\frac{dF}{dE} = f_0 \left(\frac{E}{\text{TeV1}} \right)^\alpha \exp -\frac{E}{E_{\text{cut}}} . \quad (2.1)$$

and using the forward folding method are $\alpha = 2.04 \pm 0.12$ and $E_{\text{cut}} = 13.5 \pm 5.9$ TeV.

2.5 Morphology Study

The sky maps that are discussed in the following are based on the same 80h data set that was used for the SED and use an energy range of $E \gtrsim 1$ TeV. Apart from the SgrA* point-source, like in

previous measurements by H.E.S.S. and VERITAS [26, 12], the MAGIC measurements also show extended emission coming from the region along the Galactic plane. This becomes more obvious when fitting the emission within 0.12° from SgrA* source with a 2D Gaussian and subtracting it from the relative flux map (see figure 3a). The residual sky map shows significant gamma-ray excess from the location of the supernova remnant G0.9+0.1 as well as from a region $\sim 0.2^\circ$ left from SgrA* (figure 3b).

G0.9+0.1 has been previously detected in VHE gamma rays by the H.E.S.S telescope [27] and has been identified as VHE counterpart of the PWN. The second region with strong gamma-ray excess, which has not been reported in the literature to date, is seen with a local significance of more than 7σ when subtracting the contribution from SgrA* as specified above (see figure 3b)¹. This location coincides with the southern part of the large scale radio structure called “the Arc” and hence it may be physically associated with it [28]. Other possible counterparts are the super shell G0.11-0.11, also possibly interacting with the Arc [29], or the pulsar wind nebula (PWN) G0.13-0.11 [30]. It is also possible that the TeV emission is produced by the interaction of cosmic rays (e.g. accelerated in a flaring period of SgrA* in the recent past) with the dense molecular clouds in this region [31].

After fitting and removing also those two sources in a similar manner as described above, the residual flux distributes along the Galactic plane (extending from top left to bottom right of the sky map), with evidence for enhanced emission from the dense molecular clouds SgrB2 and SgrC as well as from the region of SgrD (figure 3d).

3. Conclusions

The Galactic Center has been re-observed by MAGIC during 2012-15, accumulating approximately 80 h of good quality data. These observations were carried out in order to probe for flux variability of the SgrA* TeV source during the periastron passage of the G2 gas cloud.

No variability has been detected during the years 2013/14. Apart from probing for variability, the data could also be used for a precise spectral and morphological analysis of the SgrA* point-source and its surroundings. The flux and spectral shape has been found in good agreement with measurements by other instruments. In addition, we found a significant VHE gamma-ray excess from a region 0.2 deg away from SgrA* and spatially coinciding with the Arc radio source. The significance and morphology of this potential new source will be further investigated under different assumptions for the diffuse VHE gamma-ray backgrounds in that region of the sky.

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¹A different parametrization of the diffuse background contribution may lead to different results.

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