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# Prospects and latest optical intensity interferometry results with the MAGIC and CTAO-North LST telescopes

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Along with their gamma-ray observations at very high energies (VHE;20 GeV - 100 TeV), the two 17-m MAGIC telescopes (at Roque de los Muchachos Observatory, La Palma) have also been utilized as an optical stellar intensity interferometer (SII) for the last six years. The calibration and validation of the setup, alongside the first measurement of the stellar angular diameter of 13 massive stars, were published in a performance paper in early 2024 [1]. Around the same time, the technical advancements developed for MAGIC were applied to the first Large-Sized Telescope of the northern hemisphere array of the Cherenkov Telescope Array Observatory (CTAO-North LST-1), a 23-m diameter telescope located near MAGIC. Three more LSTs should be completed beginning of 2026 and they may be equipped in the same manner as LST-1. We will focus on our first measurements with the MAGIC+LST-1 SII and our prospects for this and the MAGIC+LST1-4 SII for the study of several objects that are also known to emit in gamma rays: novae, such as the upcoming T CrB; winds from massive stars, particularly colliding-wind binaries; and Be stars which are typical companions in VHE gamma-ray binaries.

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## 1. The MAGIC Stellar Intensity Interferometer (SII)

The main objective for Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the MAGIC telescopes, is to observe the very-high-energy (VHE;20 GeV - 100 TeV) gamma-ray night-sky. In order to perform this kind of observations, IACTs make use of several technical features that make them incidentally well suited for intensity interferometry observations: they come in groups (each combination of telescopes is a different baseline and orientation), they have time resolution of nanoseconds (needed to resolve the correlation signal), they are sensitive to single photo-electrons (and therefore coherence of individual photons) and they have large reflective mirrors (more photons means more statistics and better S/N).

In recent years, the MAGIC telescopes have undergone several technical modifications to additionally act as an intensity interferometer [2–4]. A new digitizer and GPU-based real-time correlator were implemented. Also, a dedicated configuration of its Active Mirror Control to focus the light to the infinite instead of the typical altitude of Extense Atmospheric Showers of 10 km and to concentrate it into just one or two photo-multipliers (PMTs). And finally, the automatic deployment of optical filters using the white target holder, that allows the system to transform into an intensity interferometer in less than a minute and then back to VHE observations just as quickly (useful for transients). This makes the MAGIC Stellar Intensity Interferometer (MAGIC SII) an extremely high duty cycle instrument. The observations have mainly been performed during Moon breaks, which are periods with bright Moon-light conditions in which IACTs cannot perform sensitive VHE observations, but the intensity interferometer can, thanks to the optical filters that greatly reduce the amount of blue Moon-light that gets into the PMT.

The MAGIC SII setup has been thoroughly calibrated and its systematics studied. This work has crystallized in the form of a performance paper that was published in early 2024 [1]. In this paper, the sources of systematics and their contribution to the uncertainties in the correlation measurements are shown, as well as the angular diameter measurements for 9 stars consistent with measurements by other experiments in the same wavelength range (Blue, 400-440 nm). Given the agreement with other experiments and the proven understanding of the systematics, the team was able to report 13 stellar angular diameters never before measured in Blue band, for a total of 22 measured angular diameters reported. Furthermore, prospects for the MAGIC+LST-1 SII and MAGIC+4LSTs SII were presented.

## 2. Addition of LST-1 to the MAGIC SII and prospects for MAGIC+4 LSTs

In 2024, another IACT next to the MAGIC telescopes, the first Large-Sized Telescope (LST-1) of Cherenkov Telescope Array Observatory (CTAO) was added to the setup. In fact, other 3 LSTs are currently being installed in La Palma [5]. The addition was possible by implementing a few technical modifications: two filters were mounted on the white target holder, similar to the setup in each MAGIC camera, allowing to remotely place the filters in front of any pixel; one of the front-end boards was redesigned to extract a replica of the central PMT analog signal as well as an optical transmitter; and an optical fiber was routed towards MAGIC counting house and connected to the existing correlator. The addition was successful and the correlation from all three channel combinations (MAGIC 1 & MAGIC 2, MAGIC 1 & LST-1, and MAGIC 2 & LST-1) is detected as can be seen on the left side of Fig. 1, proving that the implementation is not only possible but also easily scalable.

There are some hardware differences between MAGIC and LST-1 that make the addition of LST-1 very beneficial to the interferometer: the LST-1 mirror dish is 23 m in diameter instead of 17 m, so the mirror area is much larger (370 m$^2$ vs 236 m$^2$), also the photo-detectors quantum efficiency of $\sim$ 40% and optical efficiency of $\sim$ 60% are better than those of the MAGIC telescopes. This allows to observe fainter objects and detect correlation signal within less observing time. Not only that, but the distance and relative position of the telescopes allow to access longer baselines (from 86 m to  150 m for MAGIC+LST-1 SII and  250 m for MAGIC+4LSTs) and different simultaneous orientations (3 for MAGIC+LST-1 SII and 15 for MAGIC+4LSTs), which are needed to measure smaller objects and objects without circular symmetry. These characteristics translate into an increase in sensitivity of factor 4 and a factor 10 if 4 LSTs are added instead, being able to achieve a relative uncertainty in the angular diameter of 10% in just 2.5 h for stars up to B magnitude ~3.2, ~5 and ~6 respectively, as shown in Fig. 13 of [1]. The current setup consists of one correlator with 4 channels, which is enough for the MAGIC+LST-1 SII since it only needs 3 channels, but adding three telescopes for the MAGIC+4LSTs SII implies adding at least two more channels (6 in total). One or two pixels per telescope are needed to perform systematic studies and calibration, but the pixels used for calibration and monitoring of the night-sky background do not need to be connected to the correlator.

The setup is being tested and calibrated. A few measurements of calibrator stars from MAGIC SII performance paper in the Blue band and other stars measured by CHARA in the near-infrared have been compared with new measurements with the MAGIC+LST-1 SII, as shown in Fig. 1. The great accordance between all of them shows that the setup is indeed meeting the expectations.

### 2.1 Science cases with current Stellar Intensity Interferometers

The prime targets for the use of the intensity interferometry technique at baselines of ~100 m are main sequence stars of angular diameters between 0.5 and 2 milliarcseconds (for reference, the Moon has an average angular diameter of $\sim$ 30 arcmin while Sagittarius A* is $\sim$ 50 microarcseconds). These are generally main sequence massive stars. The most simple scenario is the determination of their stellar radii by fitting the spatial coherence measurements to an uniform disk model. By measuring the angular diameter of a star of known distance one can obtain an independent measurement of the physical star radius that can be used to test different stellar models and determine other physical parameters like mass, age or temperature.

With the addition of LST-1 to the MAGIC SII and the possibility to add 3 more LSTs in the future, new science cases can be explored.

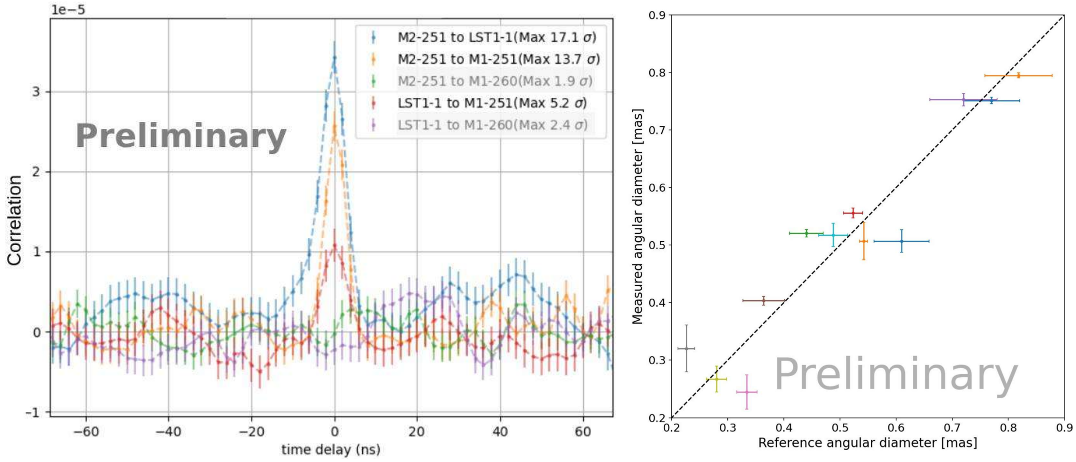


**Figure 1:** Left: significant measurement of correlation in three channels simultaneously: blue MAGIC 2 with LST-1, orange MAGIC 2 with MAGIC 1 and red LST-1 with MAGIC 1. Right: angular diameter measurements of 12 stars, comparing the measurements from MAGIC+LST-1 SII with MAGIC SII [1] (Blue band) and CHARA [6] (Near-Infrared) as reference values.

### 2.2 Novae

By studying novae one can study proton acceleration and their contribution to cosmic rays. One of the biggest unknowns when observing these events in VHE is the dominance of hadronic or leptonic mechanisms in the first moments of the explosion, hence the necessity of observing them during the optical rise. If VHE measurements are interleaved with SII observations during the first few minutes and hours, it would be possible to measure the size of the expanding shell, hence constraining leptonic emission models.

Since MAGIC+LST-1 SII has the unique characteristic of being able to switch in a matter of seconds or minutes between VHE and SII observations, this is a science case worth exploring with the setup. As it is shown in Fig. 2, depending on different combinations of evolving angular diameter (different for different shock velocity) and brightness, our simulations show that both setups, MAGIC+LST-1 SII and MAGIC+4LSTs SII, would be able to measure the shape and size of the shell for several hours after the explosion.

### 2.3 Be stars

In most VHE gamma-ray binaries, particles are accelerated in the shock between a pulsar wind and the wind of the companion star. Said companion is usually a massive star, and in most cases, a Be star. Be stars are a kind of fast rotating star, with a few spectral particularities, mostly due to the presence of a disk. Fast rotating stars are stars that spin so rapidly that the photosphere becomes oblate. The effective gravity decreases towards equatorial regions (gravity darkening), even producing mass loss that form circumstellar disks. These kind of stars when observed in the Fourier space would not present a radially symmetric pattern but an elliptical one, allowing to measure a changing angular diameter and therefore oblateness. By measuring the oblateness of Be

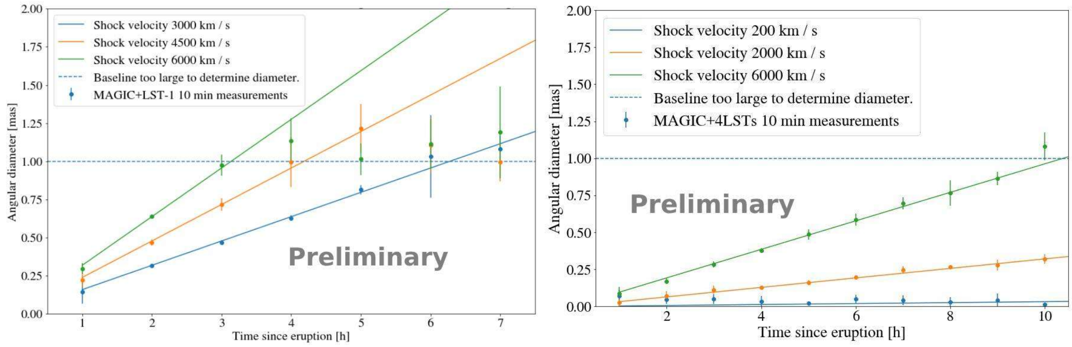


**Figure 2:** Left: Simulated measurements in snapshots of 10 min performed with MAGIC+LST-1 SII of a nova explosion of 3.3 Bmag at a distance of 3 kpc for shock velocities of 3000, 4500 and 6000 km/s. Right: Simulated measurements in snapshots of 10 min performed with MAGIC+4LSTs SII of a nova explosion of 5.5 Bmag at a distance of 3 kpc for shock velocities of 200, 2000 and 6000 km/s. For both cases, the best results are obtained up to ~1 milliarcsecond of angular size.

stars one can gain insight into the mass-loss rate and the evolution of the disk, which directly relates to VHE emission when interacting with the wind of the companion (when present).

Thanks to the implementation of the new MAGIC+LST-1 SII setup that allows to probe longer baselines and different orientations, the measurement of the shape of one such star has been possible: gamma Cassiopeiae ($\gamma$ Cas). This kind of systems are believed to host a Be star together with a white dwarf, and could emit X-rays. MAGIC SII has been collecting data between 2022 and MAGIC+LST-1 SII since 2024. The preliminary results from the analysis of MAGIC SII data (~55h) and MAGIC+LST-1 SII data (~2h) 2024 data are shown in figure 3. The preliminary values are in accordance with expected values from literature and also with equivalent measurements performed between 2023 and 2024 by VERITAS SII [7]: angular diameter of the major axis of 0.59 ± 0.01 mas, ratio between minor and major axes of 0.76 ± 0.02 and position angle of the equator of 34 ± 3 deg (only statistical uncertainties taken into account for the three quantities). Moreover, as shown by the right side of Figure 3, the oblate uniform ellipse model is preferred over the non-oblate uniform disk model: $\chi^2_\nu = 1.13$ for the oblate model and $\chi^2_\nu = 2.73$ for the non-oblate model. More complex models including gravity darkening are being studied for future publication.

With the addition of the other 3 LSTs to the setup, we would be able to obtain similar results and uncertainties for a larger sample of fast rotating stars up to B magnitude ~ 6, as shown for 5h simulations of a 5.45 Bmag fast rotator already shown in [8].

### 2.4 Colliding-wind binaries

Wind-wind collision in massive star binary systems can lead to high temperature shocks. These shocks can produce radio and optical emission as well as X-rays or even VHE gamma rays. Therefore, studying the size and placement of the shocks can help to better constrain current hydrodynamic models. This is in principle possible since colliding winds produce emission lines that can be singled out. Not only that but clumps from within the winds and they are expected to evolve

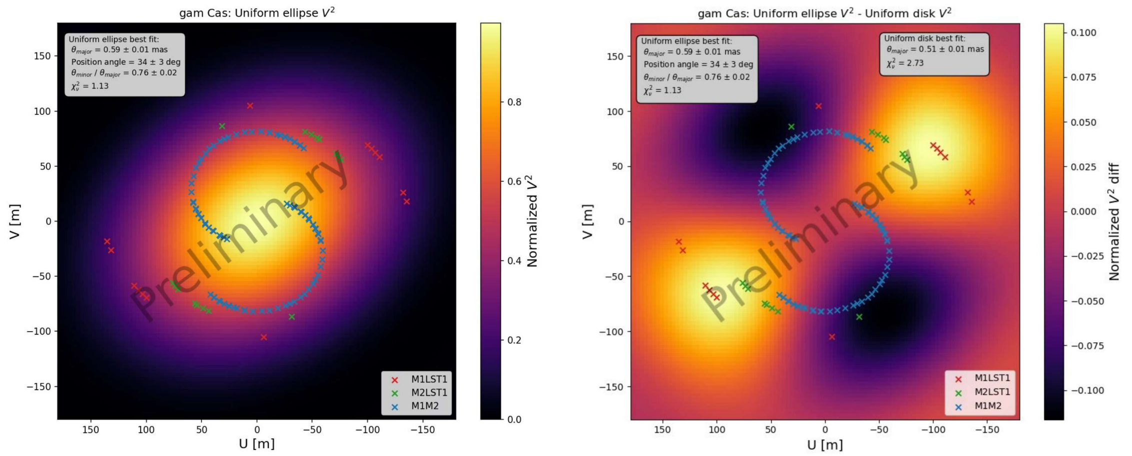


**Figure 3:** Left: UV plane (Fourier space) showing the reconstructed spatial coherence or normalized squared visibility for the star $\gamma$ Cas, along with the position of the measurements for every combination of MAGIC+LST-1 SII from 2024. The results for the major axis, axis ratio and position angle are also shown in the legend, along with a goodness of fit that shows that the oblate uniform ellipse model is preferred over the non-oblate uniform disk model. Right: difference in normalized squared visibility between the uniform ellipse model and the uniform disk model.

with time. One of these systems is $\gamma^2$ Vel, and was already studied with the Narrabri SII, measuring the size and roughly the shape of the emission region [9]. The benefits of combining intensity interferometry with spectroscopy and photometry are clear, expanding the parameters that can be constrained and studied, such as the physical radii (depending on the distance), absolute magnitude, surface gravity or effective temperature.

## 3. Conclusions

MAGIC and CTAO-LST collaborations are working together, devoting time and effort to achieve the most sensitive setup possible with no negative impact to VHE observations. The compared measurements of calibrator stars proves that we understand the setup and it is working as expected. The successful measurement of the shape of the fast rotator $\gamma$ Cas is just one of the promising science cases that we have begun or continued to explore. Synergies between VHE gamma-ray astronomy and optical intensity interferometry are very clear and further strengthen the case for this technique to be implemented in future VHE gamma-ray observatories like CTAO.

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