

The potential for intensity interferometry with γ -ray telescope arrays

W. J. de Wit^{*}, S. Le Bohec[†], J. A. Hinton^{*}, R. J. White^{*}, M. K. Daniel^{*} and J. Holder^{**}

^{}School of Physics and Astronomy, University of Leeds, LS2 9JT, UK*

[†]Department of Physics, University of Utah, 115 S 1400 E, Salt Lake City, UT 84112-0830, USA

*^{**}Department of Physics and Astronomy, University of Delaware, Newark, Delaware, USA*

Abstract. Intensity interferometry exploits a quantum optical effect in order to measure objects with extremely small angular scales. The first experiment to use this technique was the Narrabri intensity interferometer, which was successfully used in the 1970s to measure 32 stellar diameters at optical wavelengths; some as small as 0.4 milli-arcseconds. The advantage of this technique, in comparison with Michelson interferometers, is that it requires only relatively crude, but large, light collectors equipped with fast (nanosecond) photon detectors. Ground-based γ -ray telescope arrays have similar specifications, and a number of these observatories are now operating worldwide, with more extensive installations planned for the future. These future instruments (CTA, AGIS, completion 2015) with 30-90 telescopes will provide 400-4000 different baselines that range in length between 50 m and a kilometre. Intensity interferometry with such arrays of telescopes attains 50μ -arcsecond resolution for a limiting $m_v \sim 8.5$. Phase information can be extracted from the interferometric measurement with phase closure, allowing image reconstruction. This technique opens the possibility of a wide range of studies amongst others, probing the stellar surface activity and the dynamic AU scale circumstellar environment of stars in various crucial evolutionary stages. Here we focus on the astrophysical potential of an intensity interferometer utilising planned new γ -ray instrumentation.

Keywords: Intensity interferometry, Atmospheric Cherenkov telescopes

PACS: 95.55.Br, 95.55.Ka

INTRODUCTION

Optical intensity interferometry (I.I.) offers some considerable advantages over Michelson interferometry in terms of complexity, cost and wavelength coverage. Therefore, whilst so far successfully realised for only one astrophysical instrument (the Narrabri interferometry of Hanbury Brown et al. [1]), it has enormous potential for future instruments. Several years ago it was recognised that the optical requirements for an intensity interferometer match rather closely those for the arrays of Cherenkov telescopes used in ground-based γ -ray astronomy [2], namely very large mirrors and modest optical quality. Furthermore, it seems relatively straightforward to 'share' the optical systems of such a telescope array between these two activities. As large arrays of such γ -ray telescopes are now being planned, it seems timely to revisit this possibility. The technical details of this approach are described in a companion paper in these proceedings (Le Bohec et al). Here we focus on the planned new instrumentation and on the astrophysical potential of an intensity interferometer utilising such a telescope array.

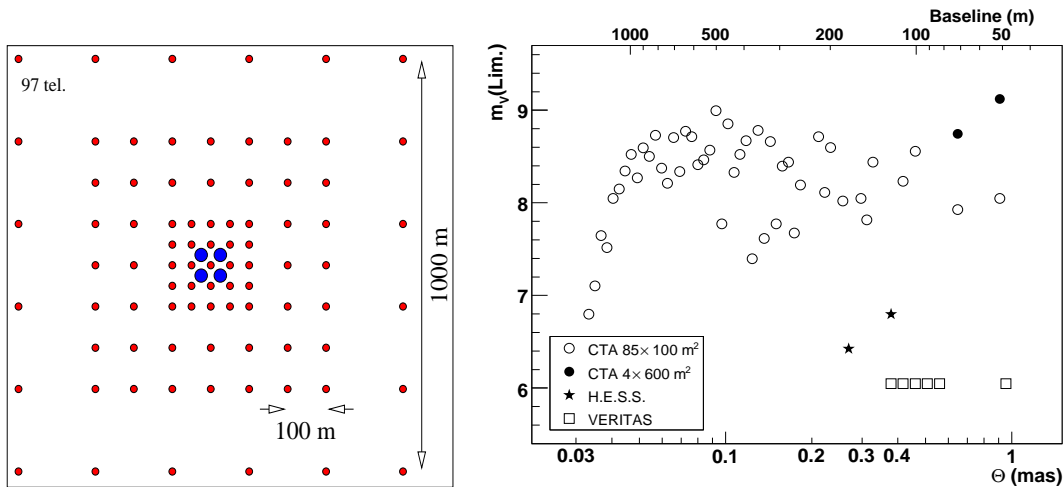


FIGURE 1. *Left:* Proposed lay-out for the future CTA. The small dots are the 85 100m^2 dishes, the large dots are the 4 600m^2 dishes. *Right:* I.I. with CTA sensitivity estimate as function of the 47 non-redundant baselines for a 5σ detection, in a 5 hours integration on a star with 50% visibility. Final values depend on signal bandwidth and CTA design details (see Le Bohec et al., these proceedings).

CHERENKOV TELESCOPE ARRAYS

The current operational Imaging Atmospheric Cherenkov Telescope (IACT) arrays such as VERITAS [3] and H.E.S.S. [4] consist of four 12 m ($\sim 100\text{m}^2$) telescopes compound mirrors producing on-axis point-spread-functions of $\text{FWHM} \approx 0.05^\circ$. These telescopes are designed to image the Cherenkov light produced in the electromagnetic cascades initiated by very-high-energy γ -rays (typically $10^{11} - 10^{13}$ electronVolt), and have been used in the past to do optical measurements. For example the telescopes of H.E.S.S. have been used to measure the optical light-curve of the Crab pulsar [5] and to search for ultra-fast optical transients from binary systems (Deil et al. these proceedings).

Two initiatives currently exist aiming for an order of magnitude improvement in the sensitivity of IACT arrays. To achieve this, both projects aim to construct a large array with more and/or larger telescopes, covering an area of approximately 1km^2 . Larger light collecting dishes, important for I.I. sensitivity, are technically feasible and are currently used by the single dish MAGIC telescope (17 m) [6]. A 30 m dish is under construction as part of the second phase of the H.E.S.S. project. AGIS (Advanced γ -ray Imaging System) [7] is the American-proposed next generation 1km^2 instrument. The Cherenkov Telescope Array (CTA) [8] is the European equivalent. The science goals of these projects are extremely diverse, covering many aspects of both galactic and extra-galactic high energy astrophysics as well as topics from particle physics and cosmology. The left panel of Fig. 1 illustrates a potential layout of CTA with simulated performance that meets the goal sensitivity for γ -ray astronomy [9]. Some 85 identical telescopes provide 3570 potential pairings, providing 47 closely-spaced, unique baselines ranging between 50 and 1000 m. The idea of using CTA as an intensity interferometer is currently under discussion within the consortium.

SCIENCE OBJECTIVES

Intensity Interferometry at a future IACT is likely to operate in the visual wavelength region. Science objectives are therefore similar but not the same as future 1 km baseline Michelson interferometers such as *Ohana* [10] which operate in the *K* band. Limiting m_v of a CTA concept is illustrated in the right panel of Fig. 1. Targets are limited to a $m_v \approx 8.5^m$ for a $S/N = 5$, and a 5 hours integration in case of 50% visibility (see Le Bohec et al., these proceedings). These specifications allow important interferometric studies regarding binary stars, stellar radii and pulsating stars with unprecedented resolution on scales of 10s of μ -arcseconds. Below we highlight three of the potential science topics.

Star formation. Key questions relating to the physics of mass accretion and pre-main sequence (PMS) evolution can be addressed by means of very high resolution imaging as provided by the next generation IACTs and I.I. They involve the absolute calibration of PMS tracks, the mass accretion process, continuum emission variability, and stellar magnetic activity. The technique will be able to resolve features on the stellar surface. Hot spots deliver direct information regarding the accretion of material onto the stellar surface. Cool spots on the other hand may cover 50% of the stellar surface, and are the product of the slowly decaying rapid rotation of young stars. Imaging these cool spots will constrain ideas regarding the interplay of rotation, convection and chromospheric activity and may also provide a direct practical application in the explanation for the anomalous photometry observed in young stars [11]. In practise about 50 young stars with $m_v < 8^m$ are within reach of future IACTs. In the last decade several young coeval stellar groups have been discovered within ~ 50 pc of the sun. Famous examples are the TW Hydra and β Pic comoving groups. The majority of the spectral types within reach lie between A and G-type. Their ages lie within the range 8 and 50 Myr (for an overview see [12]), ensuring that a substantial fraction of the low-mass members are still in their PMS contraction phase. Measurements of their angular size can be used in the calibration of evolutionary tracks, fundamental in deriving the properties of star forming regions and young stellar clusters. The proximity of the comoving groups ensures that their members are bright and also makes these groups relatively sparse, making them unconfused targets, even given the large PSF of $\sim 3'$. This sparseness is also the reason for incomplete group memberships, making it likely that the number of young stars known to lie close to the sun will increase in the years to come.

Distance scale. Measuring the diameters of Cepheids is a basic method with far reaching implications. A radius estimate of a Cepheid can be obtained using the Baade-Wesselink method. The Baade-Wesselink method relies on measurement of the ratio of the star size at times t_1 and t_2 , based on the luminosity and colour. Combining this with the measurement of the radial velocity, delivering the difference in the radius between t_1 and t_2 , one can derive the radius of the Cepheid. Combining I.I. angular size measurement with the radius estimate using the Baade-Wesselink method one obtains the distance to the Cepheid (see [13]). This allows the calibration of the all important Cepheid period-luminosity relation using local Cepheids. A count of Cepheids observed with Hipparcos [14] shows that at least 60 Cepheids with $m_v < 8^m$ are within reach of future I.I.-IACTs.

Rapidly rotating stars. As a group classical Be stars are particularly well-known for their proximity to break-up rotational velocities as deduced from photospheric absorption lines. In addition these stars show Balmer line emission firmly established as due to gaseous circumstellar disks, that appear and disappear on timescales of months to years. These two properties are somehow related, but many open questions regarding the detailed physical processes at play still exist. The Be-phenomenon is an important simply due to the number of stars and the range of stellar physics involved (the fraction of Be stars to normal B-type peaks at nearly 50% for B0 stars, [15]). Absorption lines will however never provide the final answer to their actual rotational velocity due to strong gravity darkening at the equator and brightening at the poles. Direct measurement of the shape of the rotating star is not hampered by gravity darkening, and provides a direct indication of the rotational speed (see e.g. α Eri with the VLTI, [16]). The Be star disk formation and dissolution activity is little understood. Photometric observations of Be star disks seem to indicate that they may actually evolve into ring structures before disappearing into the interstellar medium (e.g. [17]). Bremsstrahlung in the disk can constitute $\sim 30\%$ of the total light in V-band [15]. There are about 300 Be stars brighter than $m_v = 8^m$, roughly corresponding to a distance limit of 700 pc [18], signifying that Be star phenomena can be probed in depth with IACT based I.I.

CONCLUSION

Intensity Interferometry using the telescopes of the future IACT arrays CTA and/or AGIS has the potential to make a major impact in several areas of stellar astrophysics and beyond. Whilst much research and development in this area is still required, such a major instrument could be realised at rather modest cost and as early as 2015.

REFERENCES

1. R. Hanbury Brown, and R. Q. Twiss, *Nature* **178**, 1046 (1956)
2. S. Le Bohec, and J. Holder, *ApJ* **649**, 399 (2006)
3. J. Holder, et al., *Astroparticle Physics* **25**, 391 (2006)
4. J. A. Hinton, *New Astronomy Review* **48**, 331 (2004)
5. J. Hinton, G. Hermann, P. Krötz, and S. Funk, *Astroparticle Physics* **26**, 22 (2006)
6. J. Cortina, *Ap&SS* **297**, 245 (2005)
7. <http://cherenkov.physics.iastate.edu/wp/>
8. <http://www.mpi-hd.mpg.de/hfm/CTA/>
9. K. Bernlöhr, et al. in *Proc International Cosmic Ray Conference*, (2007)
10. G. S. Perrin, et al. in *SPIE Volume 5491*, 391 (2004)
11. J. R. Stauffer, et al., *AJ* **126**, 833 (2003)
12. B. Zuckerman, and I. Song, *ARA&A* **42**, 685 (2004)
13. D. Sasselov, and M. Karovska, *ApJ* **432**, 367 (1994)
14. M. A. T. Groenewegen, *A&AS* **139**, 245 (1999)
15. J. Zorec, and D. Briot, *A&A* **318**, 443 (1997)
16. A. Domiciano de Souza et al. , *A&A* **407**, L47 (2003)
17. W. J. de Wit, et al., *A&A* **456**, 1027 (2006)
18. <http://www.astrosurf.com/buil/us/becat.htm>