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TOWARDS A SQUARE-KILOMETER OPTICAL TELESCOPE: THE POTENTIAL OF INTENSITY INTERFEROMETRY

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RESUMEN

Líneas de base óptica de escala kilométrica se requieren para distinguir características en discos estelares. La *interferometría intensa* desde tierra es insensible a ambas, turbulencia atmosférica e imperfecciones en los telescopios ópticos, permitiendo observaciones de largas líneas de base aún en cortas longitudes de onda óptica. Estas requieren colectores de gran flujo, los cuales se encuentran en configuraciones de telescopios de Cherenkov atmosféricos que estudian rayos gamma energéticos. Detectores de alta velocidad y manejo de señales digitales permiten sintetizar muchas líneas de base en programas computacionales entre numerosos pares de telescopios, reviviendo la técnica pionera desarrollada por Hanbury Brown & Twiss.

ABSTRACT

Kilometric-scale optical baselines are required for imaging features across stellar disks. Ground-based *intensity interferometry* is insensitive to both atmospheric turbulence and to imperfections in telescope optics, permitting long-baseline observations even at short optical wavelengths. Its required large flux collectors are becoming available as arrays of atmospheric Cherenkov telescopes set up for studying energetic gamma rays. High-speed detectors and digital signal handling enable very many baselines to be synthesized in software between numerous pairs of telescopes in a digital revival of a technique once pioneered by Hanbury Brown & Twiss.

Key Words: instrumentation: high angular resolution — instrumentation: interferometers — stars: individual

1. HIGHEST SPATIAL RESOLUTION

The science cases for constantly higher angular resolution in astronomy are overwhelming, driving many instrumentation developments. Tantalizing results from current optical interferometers –revealing circumstellar shells or oblate shapes of rapidly rotating stars– show how we are beginning to view stars as a vast diversity of objects, and a great leap forward will be enabled by improving angular resolution by just another order of magnitude. Bright stars typically have angular sizes of a few milliarcseconds, requiring interferometry over hundreds of meters to enable surface imaging. However, amplitude/phase-interferometers require optical precision to within a fraction of an optical wavelength, while atmospheric turbulence makes their operation very challenging for baselines much longer than 100 m, and at shorter visual wavelengths.

While space-based interferometers may be a longer-term solution, they are constrained by complexity and cost. However, for some classes of brighter objects (especially hot stars), comparable imaging could be realized rather soon by ground-based *intensity interferometry*, measuring the second-order (i.e., intensity-, not phase-) coherence of light (e.g., Labeyrie et al. 2006).

The great observational advantages are the lack of sensitivity to either atmospheric disturbances or to imperfections in telescope optics. This comes about from the electronic (rather than optical) connection of telescopes: the noise budget relates to electronic timescales of nanoseconds (and light-travel distances of centimeters or meters) rather than those of the light wave itself. For realistic time resolutions of 1–10 ns, light-travel distances are 0.3–3 m, and optical errors of maybe one tenth of those can be tolerated. The insensitivity to atmospheric seeing enables very long baselines, observations at short optical wavelengths, and observing near the horizon (thus accessing a greater part of the sky).

An intensity interferometer uses pairs of telescopes which measure the random and very rapid [quantum] fluctuations in the intensity of light from some star. Telescopes close together measure the same signal, but when further away, the fluctuations become de-correlated. The second-order spatial coherence is obtained from the correlation between the intensity fluctuations measured in each of the telescopes, and how this correlation gradually changes for different telescope separations. Measuring this second-order quantity requires a high photon flux

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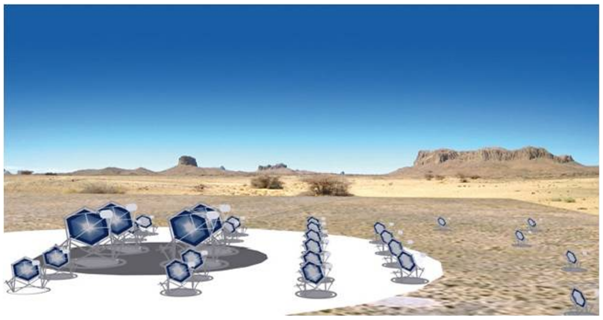

Fig. 1. Artist's vision of *CTA*, the future *Cherenkov Telescope Array*. When suitably equipped, such kilometric-scale facilities will enable submilliarcsecond imaging of the surfaces on hotter stars. (*ASPERA*; D. Rouable).

which constrains the method to bright (and hot) objects, with an estimated magnitude limit $m_V \approx 9$.

For ordinary light with a "random" distribution of photons in time (e.g., thermal emission from stars), simple relations exist between the first-order coherence function (the visibility measured in phase interferometers) and the second-order functions, yielding stellar parameters from intensity-correlation measurements (Dravins 2008). Image reconstruction becomes feasible in systems with many telescopes by applying mathematical relations between the many Fourier components of the image, and their phases.

2. CHERENKOV TELESCOPES: FIRST KILOMETRIC OPTICAL IMAGERS?

The required facility is a grid of large light collectors spread over a significant area, such as the atmospheric Cherenkov telescopes being set up for studying energetic gamma-ray sources. In particular, planned facilities such as *CTA*, the *Cherenkov Telescope Array*, or *AGIS*, the *Advanced Gamma-ray Imaging System*, will have many large telescopes distributed over some square km or more, and their unprecedented optical collecting area forms an excellent facility for sub-milliarcsecond optical imaging, enabling a digital revival of a method originally developed a long time ago (Hanbury Brown 1974).

This potential has now been realized by several workers (Dravins & Le Bohec 2008; Le Bohec & Holder 2006; Le Bohec et al. 2008; Ofir & Ribak 2006a,b); a first conference was held in Salt Lake City in early 2009; an IAU working group has been constituted, and several papers published. Outstanding tasks include: prototype instrumentation and test observations; evaluating alternative data handling in either on-line hardware or off-line software; demonstrating full image reconstruction in the presence of noise; selecting the most promising astrophysical targets and their spectral features; and assessing the experience from analogous intensity interferometry in high-energy particle physics.

DISCUSSION

Florentin Millour: *Is there an equivalent of bispectrum, triple correlation or closure phase in intensity interferometry?* — Actually, yes, i.e., something equivalent to closure phase exists between intensity fluctuations correlated between triples of telescopes. However, the information content in such and other higher-order correlations has not yet been much explored for possible astronomical applications (possibly, such issues may have been analyzed in intensity interferometry of bosons in high-energy particle physics).

Gordon Robertson: *Can you say how hot a source would have to be to give acceptable S/N if the resolution was 50–100 μas?* — For such resolutions, the Fourier transform of the source's intensity distribution must have sensible components on the scale of, say, one km, while at the same time being hot and bright enough to give an adequate photon flux. This depends not only on the source brightness but also on its spatial structure. If a star is crossed by a narrow obscuring disk, that may throw power into high Fourier frequencies corresponding to such baselines.

Markus Schöller: *Do you have to scale by a factor of 2500 in integration time when going from 50% to 1% visibility?* — In principle, yes. The S/N ratio improves with the square root of the integration time but depends also on other parameters such as the electronic time resolution, telescope collecting area, and the number of optical spectral channels. In measuring small visibilities, all such parameters may have to be optimized, rather than merely increasing the integration time.

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