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Hypertelescope imaging

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Single aperture interferometry by means of speckle imaging has made inroads in several important fields in astrophysics. In recent years, the adaptive optics system at the telescope has produced spectacular results. However, the aperture of a telescope limits its resolving capacity. A diluted array of two or more telescopes is required to measure the brightness distribution across most stellar sources and many other objects of astrophysical importance. Such a technique, known as aperture synthesis, provides greater resolution of images than is possible with a single member of the array. Following the success of Interferometre a deux Telescope (I2T) and Grand Interferometre a deux Telescope (GI2T), the interferometry with phased arrays of multiple large sub-apertures has become a reality. These instruments are used to obtain results from the area of stellar angular diameters with implications for emergent fluxes, effective temperatures, luminosities and structure of the stellar atmosphere, dust and gas envelopes, binary star orbits with impact on cluster distances and stellar masses, relative sizes of emission-line stars and emission region, stellar rotation, limb-darkening, and astrometry. However, in order to obtain snapshot images of the astronomical sources, many-aperture optical array with arbitrarily diluted apertures is required to be built. The concept of `hypertelescope' approach to imaging, which is viewed as a simple modification of the classical Fizeau interferometer by employing pupil densification, has a vast potential, since large array of relatively small apertures is easy to implement. In view of the present scenario, after a brief presentation on the interferometric techniques, the current trend and the path to future progress in optical interferometry using hypertelescope concept will be discussed.

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1 Introduction

Knowledge of atmospheric turbulence have led to the discovery of speckle interferometry by Labeyrie [1]. The image of a star obtained through a large telescope looks ‘speckled’ or grainy because different parts of the image are blurred by small areas of turbulence in the Earth’s atmosphere. The speckle interferometry is one of the most promising developments in the field of observational astronomy in visible waveband, which accomplishes entirely by a posteriori mathematical analysis of numerous images of the same field, each taken over a very short time interval. It became an extremely active field scientifically with important contributions made to a wide range of topics in stellar astrophysics.

Though the angular resolution capabilities in astronomy differ across the electromagnetic spectrum, it is limited with the diameter of the single aperture. The resolution improves if the baselines are extended by using diluted aperture. Spectacular progress has been witnessed in the case of the radio interferometry in which very long baseline interferometry (VLBI) achieves the maximum baselines. The advantages of interferometry in radio astronomy with large array of telescopes caught the attention of astronomers working on optical and infrared wavelength bands. However, its major advantages over the optical counterpart are: (i) uniform phase over individual apertures, (ii) time integration, (iii) phase stability of delay lines and (iv) electric delay lines. The beam separation and heterodyne technique to reduce the high frequency signal to an intermediate one can be employed as well; the advantages of the heterodyne technique in the case of beam recombination are: a larger coherence length, a simplification of the transport of the signal from the collector to the recombiner. Also, it is possible to preserve phase information for widely separated dishes by using very accurate clocks and time markers in the data streams. On the other hand, optical interferometry faces many drawbacks, such as (i) many phase cells over the pupil, hence, the size of the telescope becomes limited to the size of the atmospheric coherence diameter (Fried’s parameter), (ii) short atmospheric coherence

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time, (iii) mechanical stability of telescopes, (iv) optical delay lines, (v) beam recombination (pupil or in image plane), (vi) limited u,v-coverage, and (vii) limited accuracy on amplitude and phase estimates. It needs extreme accuracies to meet the demands of maintaining the pathlengths within the interferometer, constant to a fraction of a wavelength of light as well. These constrained Long Baseline Optical Interferometers (LBOI) to smaller baselines (~100 m). In what follows, after a brief presentation on the interferometric techniques, the optical interferometry using hypertelescope concept are enumerated.

2 Long Baseline Optical Interferometry

Long baseline optical interferometry (LBOI) uses two or more apertures to mimic the angular resolution of a single one having a diameter about the size of the separations. It came into existence in 1974 when Labeyrie [2] obtained fringes of a star, called Vega, at the Nice Observatory, using a pair of small independent telescopes. It combines the features of the Michelson design and the radio interferometer and consists of a pair of 26 cm telescopes on altitude-altitude mounts having a long coude focus. These telescopes track simultaneously the same source (star) and send the collected light to the central laboratory where the star images are superposed at the foci in order to produce Young's fringes similar to those observed by Michelson and Pease [3]. The beams from these telescopes are recombined in an image plane after reconfiguring the pupils. Fringed speckles are visualized when a speckle from one telescope is merged with the speckle from other telescope. These fringed speckles are dispersed and the spectra are recorded at short-exposure using a photon counting detector [4 and references therein]. The beam-recombining optical devices were kept on a computer controlled motor driven carriage parallel to the baseline. This carriage moves along the telescopes to maintain constant zero optical path difference (OPD) that changes due to diurnal motion, within the coherence length between the two beams.

Following its success, another interferometer called Grand Interferometre a deux Telescope (GI2T) has also been developed [5]. Success of developing two-telescope interferometry has made it possible to obtain a very high resolution of the order of a few milliarcseconds. This technique has addressed subjects such as star surface imaging, close binaries, circumstellar environment. One of the noted results was the achievement of resolving the rotating emission envelope of hot star γ-Cassiopeia [6], demonstrating the potential of observations that combines spectral and spatial resolution. However, interferometers with two telescopes provides the angular size and shape of the source, but cannot reconstruct the angular distribution across an asymmetrical source without ambiguity. For a binary component, such an instrument produces double images with 180 degree ambiguities; one of the two images on either side of the central one that represents the primary component, is the secondary component.

This limitation is possible to circumvent in systems with a larger number of telescopes, where sampling across all possible pairs may permit the reconstruction of high resolution images. Each pair of telescopes in the array yields a measure of the amplitude of the spatial coherence function of the object at a spatial frequency $\mathbf{B}/\lambda$, where $\mathbf{B}$ is the baseline vector and λ the wavelength. According to the van Cittert-Zernike theorem [7], if the number of samples of the coherent function can be made large, the spatial frequency spectrum of the object can be reconstructed. With optical aperture synthesis imaging, the measurement of stellar parameter is extended to the reconstruction of high resolution stellar images. This technique has been successfully implemented by Baldwin et al. [8] in the visible band by reconstructing an image of an object using Cambridge Optical Aperture Synthesis Telescope (COAST). Subsequently, several such arrays with multi-telescopes have been developed [9, 10 and references therein]. However, interferometer like Very Large Telescope Interferometer (VLTI) uses large- and medium-sized outrigger telescopes. Recombining large and small telescopes is a difficult task since the signal-to-noise ratio is determined by the smaller ones. These instruments have specific capabilities and limitations. Limitations being small baselines, a few telescopes, and limited potential for expansion. The concept of 'hypertelescope technique' seems to be a viable alternative for imaging.

3 Principle of hypertelescope

The lack of spatial frequency coverage, the existing LBOIs have become inefficient for direct imaging. In this respect, the concept of the 'densified-pupil imaging interferometry' is appealing. Conceptually, it differs from the Fizeau interferometry in which most energy goes in a broad diffractive halo rather than in a narrow interference peak if the sub-aperture spacing is large compared to their size. This precludes obtaining usable snapshot images with kilometric or megametric arrays in space. The procedure involves in this case is that of adding the fields from each aperture in a focal plane. Densifying the exit pupil, i.e., distorting it to increase the relative size of the sub-pupils, in such a way that the pattern of sub-aperture centers is preserved, concentrates the halo and intensifies the image [11]. In the recombination plane, the distance between two pupils corresponding to two telescopes is minimized to become about equal to their diameter. This principle can be a optimal solution for instruments with many telescopes and short baselines.

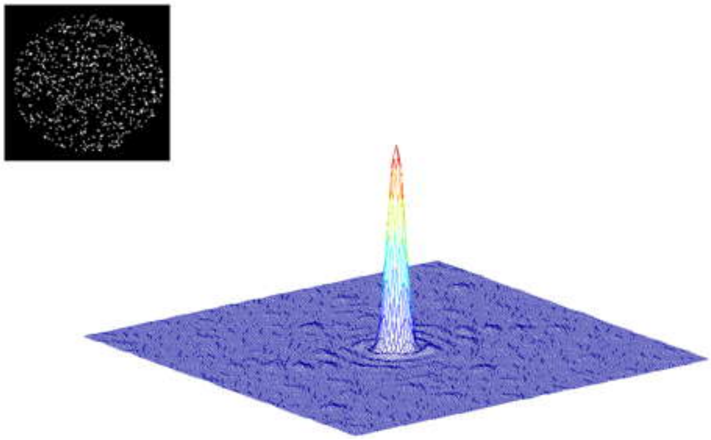

Fig. 1. Top panel: Arrangement of 775 small apertures. Bottom panel: The point spread function of such an arrangement.

A large array, comprising of small apertures, shaped like Arecibo radio telescope dish, is an alternate method. In this, many small mirrors are distributed on a spherical surface. A camera and focal corrector of the spherical aberration are suspended at the focal sphere. It exploits a natural depression with an emphasis on interferometric imaging. The spherical geometry reduces the amount of pathlength compensation required in re-pointing the interferometer array. A prototype instrument has already been developed [12] and a large-scale version like CARLINA 2 is under development [13]. Carlina can have a broad primary field, but requires correcting optics near the primary focal plane to compensate the spherical aberration. Such an instrument has the following advantages: (1) it can accomodate a large number of small mirrors, (2) it has a simple optical scheme with respect to multi-telescope interferometers, (3) it does not require delay lines, and (4) its simplified optics makes the metrology and coherence adjustment much easier and is more accurate [14]. The focal point optics is based on a Mertz corrector and a pupil densifier. A CCD camera is placed at the densified focus. An AO system may be placed between the Mertz corrector and the densifier. However, building such a giant system requires a crater-shaped site, and a delicate suspension of the focal optics for tracking the star image along the focal surface.

4 Conclusions

The field of research that has benefited the most from the speckle interferometric technique using large-/moderate-sized single telescopes, and shall continue to benefit, is the origin and evolution of stellar systems. This evolution starts with star formation, including multiplicity, and ends with the mass loss process which recycles heavier elements into the interstellar medium. Large-scale star formation provides coupling between small-scale and large-scale processes. Stellar chemical evolution or nucleo-synthesis that is a result of star formation activity further influences evolutionary process. High resolution observations are fruitful for the detection of proto-planetary disks and possibly planets (either astrometrically, through their influence on the disk, or even directly). Studies of the morphology of stellar atmospheres, the circumstellar environment of nova or supernova, Young Planetary Nebulae (YPN), Long Period Variables (LPV), rapid variability of Active Galactic Nuclei (AGN) etc., are also essential [15-17 and references therein].

Over the years optical interferometry with diluted apertures has slowly gained importance. The technological advancement made it possible to witness the speedy progress of optical interferometry using diluted apertures. The new generation interferometers with phased arrays of multiple sub-apertures, hypertelescope in particular, would provide larger collecting areas and higher spatial resolution simultaneously. Such an instrument may provide imaging and morphological informations on the faint extragalactic sources such as, galactic centers in the young universe, deep fields, and host galaxies. However, a major challenge for building a hypertelescope is the development of adaptive phasing system. Modified wave sensing techniques such as dispersed speckle analysis are planned to be used with these systems. But development and installation of such advanced methods are not available at present. In such a scenario, speckle mode observations with hypertelescope becomes a viable alternative. Even in table top versions of hypertelescope, speckle images have been observed due to phase variations in the sub-apertures. A study of speckle techniques with such systems is thus of great interest. Image processing with the bispectrum algorithm is useful for simulations involving a diluted aperture interferometry, since it is difficult to incorporate adaptive optics system in a hypertelescope. Observations may be carried out by speckle interferometry, using either a redundant or non-redundant many-element aperture.

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