Science at Very High Resolution: The Expected and the Unexpected

Prepared by USIC,
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The most important observational discoveries result from substantial technological innovation in observational astronomy.

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Cosmic Discovery

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* USIC speaks on behalf of the U.S. ground-based optical arrays, and has benefited from participation and input from more than 100 members of the scientific community.

Initiative	Decadal Cost
Optical and Infrared Interferometers	*$45M*

Excerpt from the *Moderate Initiatives* table in the 1991 AASC Decadal Report [i]

Introduction

While science is often driven toward a defined goal, progress frequently occurs almost incidentally following deployment of new technology. This effect has been systematically studied and summarized by Martin Harwit [ii], *The most important observational discoveries result from substantial technological innovation in observational astronomy*. Other authors have recognized similar impact to typically follow substantial gain in the precision of measurements of almost any parameter.

Subsequent to the 1991 Decadal recommendation for development of optical interferometry[i] (cited above), NASA, NSF, NOAO and a number of universities have sponsored a series of prototype, testbed, and finally facility class optical/IR interferometric arrays. These arrays have achieved angular resolution more than 1000× beyond the seeing limit, and more than 30× beyond the aperture limit of the largest telescopes. They have enabled a rapid growth of high resolution astronomy, and have already shown, when applying this new observational capability to science, not only the expected gains of resolution and precision, but an abundance of unexpected results.

1. Interferometry Science Productivity Today

A convenient measure to track the progress of optical interferometry is the number of publications. Figure 1 shows the integrated total count of refereed science papers in optical interferometry plotted against number of years since the first demonstration of interference between two independent telescopes (1974). Plotted on the same diagram is the integrated total of refereed publications in radio interferometry with a time shift of 32 years. The similarity of the curves for these analogous techniques suggests that the community's experience with radio interferometry may be a fair guide to the potential eventual impact of optical interferometry.

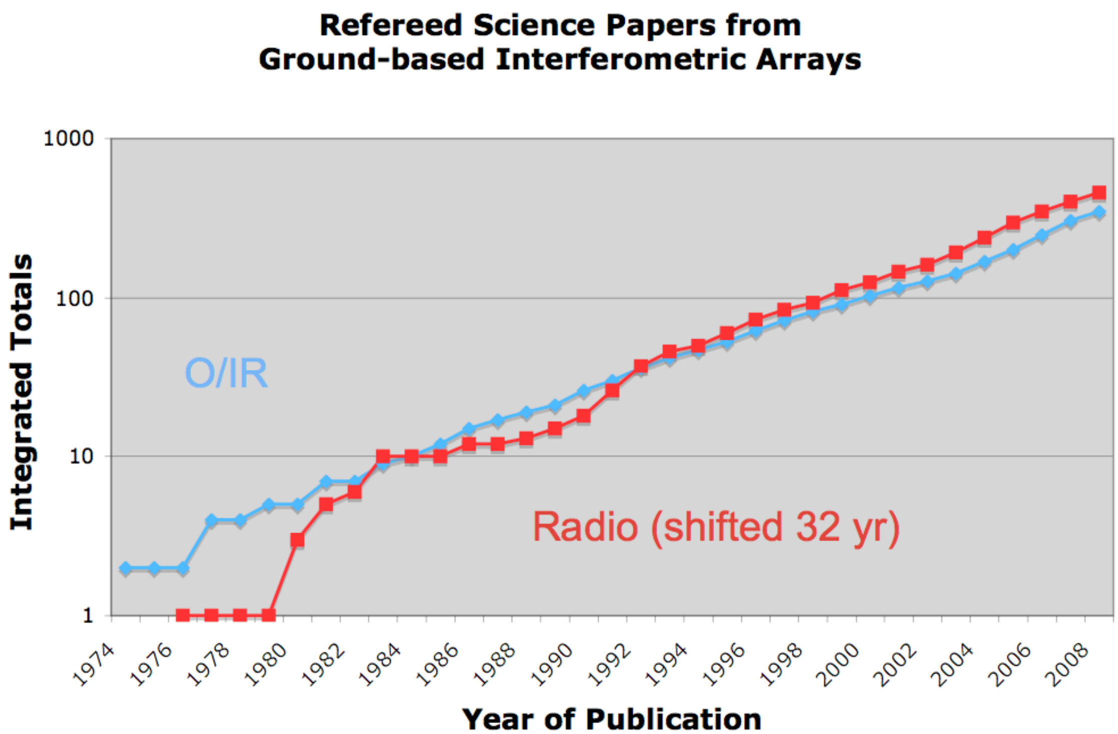

Figure 1. This chart shows the running total of refereed publications presenting new interferometric results at radio and optical wavelengths. Instrumentation and review papers have been excluded. The time axis begins in 1974 with the publication of the first two-telescope optical interferometry measurement. On this scale, the VLA will be dedicated in 2012.

Another measure of the productivity of a technique is the extent to which it provides new information. The information content of data is highest for results which are surprising or unpredictable. In a few short years of activity, primarily with simple two-telescope operation, interferometry has given us, by that criterion, a great deal of information.

3. Why this Paper?

The community has scarcely begun to scratch the surface of interferometry's potential – indeed, many of you may not be aware that arrays of telescopes operate nightly. With the potential for rapid improvements in sensitivity, imaging performance, and access, the future of interferometry should be shining brightly. However, the fact is that each of our arrays is severely under-funded, and within a small fiscal perturbation of closing its doors. We will probably lose one or more before the Astro2010 recommendations can take effect. The national investment in this technology could be lost for lack of operations funding. We take this opportunity to present a science overview of its accomplishments, as a sample and a guide to what it could deliver in the next decade, and to set the scene for a separate proposal to carry optical interferometry through the next decade and into the decades beyond.

4. The Expected and the Unexpected

This section will describe and contrast a selection of the expected and the unexpected results from the approximately one hundred refereed and published O/IR interferometric investigations of the last three years.

Young Stellar Objects – It is well known that spectral energy distributions and spectroscopy alone do not uniquely constrain disk and shell models. Interferometry (near and mid-IR) is delivering the expected spatial information required to break the degeneracy. It has settled the question of the form of Herbig Ae-Be star circumstellar material distribution (disks, not shells), and measures the disk inclination as well. It has produced precision masses for binary YSO's (Boden *et al*, ApJ, 635, 442), providing much-needed constraints on evolutionary models.

In addition to these reasonably expected results, interferometry has delivered some surprises. In T Tauri stars, vertically extended disk walls (or flaring) has been detected in younger objects (Akeson *et al.*, ApJ, 635, 1173) while continuous replenishment of grains was found in an older system (Eisner *et al.*, ApJL 637, L133). Water vapor has been observed in the habitable zone of a preplanetary disk (Eisner, Nature 447, 562), and the conversion of dust from amorphous to crystalline has been localized to the inner disk region (Ratzka *et al.*, A&A 471, 173).

In Herbig Ae-Be stars, self-shadowing and localized hot spots have been found in disks (Fedele *et al.*, A&A 491, 809; Milan-Gabet *et al.*, ApJ 645, L77). Evidence has been found for decoupling of the accretion disk gas and dust (Fedele *et al.*, A&A 491, 809), with gas inside the dust sublimation radius (Tannirkulam *et al.*, ApJ 677, L51; Kraus *et al.*, ApJ 676, 490), and for a wind launched from disks (Tatulli *et al.*, A&A 464, 55).

Active accretion has been observed in FU Ori stars (Millan-Gabet *et al.*, ApJ 641, 547), and flaring in the disks (Abraham *et al.*, A&A 449, L13).

Main Sequence Stars – Interferometric programs on MS stars have delivered the expected precision angular diameters and with these, direct determinations of T_{eff} are now limited primarily by photometry (and its absolute calibration). Limb darkening, and its variation with wavelength, is now directly measured with ease. The effects of granulation (convection) have been observed, testing 3-d hydrodynamic models (Aufdenberg *et al.*, ApJ 633, 424; Bigot *et al.*, A&A 446, 635). The distortion of rapidly rotating stars can be measured, the polar brightening observed, the mass loss disks mapped (some are irregular), and for young Be stars, the CO emission is found to arise inside the dust sublimation radius (Tatulli *et al.*, A&A 489, 1151).

But interferometry has also brought numerous surprises for main sequence stars. Interior models have more than expected difficulty with low metallicity and low mass stars (Boyajian *et al.*, ApJ 683 424; Berger *et al.*, ApJ 644, 475). And who would have expected determination of masses to 1% for single stars (Cunha *et al.*, ARAA 14, 217;

North *et al.*, MNRAS 380, L80), enabled by the combination of interferometry, asteroseismology and astrometry.

The demonstration that α Lyr is a pole-on rapid rotator shows that decades of modeling the spectrum for use as a primary standard are erroneous (Peterson *et al.*, Nature 440, 896; Aufdenberg *et al.,* ApJ 645, 664). Furthermore, α Lyr has a hot debris disk, which requires frequent replenishment (Absil *et al.*, A&A 452, 237) as do seemingly normal MS stars like τ Ceti, β Leo and ζ Lep (Di Folco *et al.*, A&A 475, 243; Akeson *et al.*, ApJ 2009 in press).

Rapidly rotating stars present the expected gravitational equatorial darkening (de Souza *et al.*, A&A 442, 567; McAlister *et al.*, ApJ 628, 439; van Belle *et al.*, ApJ 637, 494), but also several surprises, including apparent deviation of shape from the simple Roche lobe in Altair (Monnier *et al.*, Science 317, 342; Carciofi *et al.*, ApJ 676 L41). Keplerian disk rotation is found (Meilland *et al.*, A&A 464, 59), but also high velocity polar winds (Chesnau *et al.*, A&A 435, 275), Kervella *et al.*, A&A 453, 1059). MWC 297 even appears to exceed the critical velocity (Acke *et al.*, A&A 485, 209).

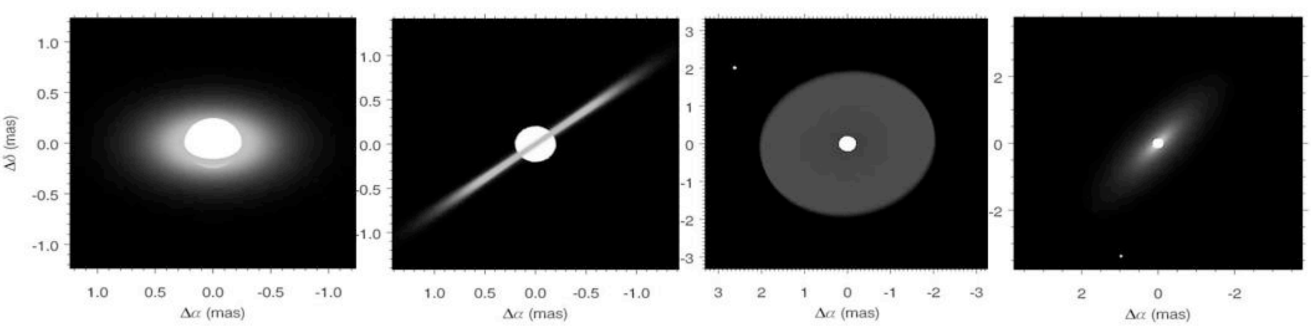

Figure 2. Parametric models of Be stars based on 2-telescope visibilities at multiple position angles. From left, γ Cas, ζ Tau, κ Dra and ϕ Per, with companion stars appearing in the latter (Gies et al., ApJ 654, 527). The models are not unique, because the observations do not constrain asymmetries, as observed with other interferometric measurement techniques (eg Vakili et al., A&A335, 261); Bério et al. A&A 345, 203).

Cepheid Stars – Interferometry, combined with precision parallaxes from GAIA and/or SIM, may be key to the improvement of Cepheid distance measurement precision from the current ~10% to a few %. Nearby Cepheids are readily resolved, with the angular diameter variation following the prediction from radial velocity, and the scale allowing the calibration of the p-factor, critical to accurate use of the Baade-Wesselink approach to distance measurement. Interferometry has already revealed some complexity of Cepheids that was largely overlooked by classical techniques. Unexpectedly, some of our nearby prototype Cepheids are found to have circumstellar material which must be understood and accounted for (Kervella *et al.*, A&A 448, 623; Mérand *et al.*, A&A 453, 155 and ApJ 664, 1093) to exploit photometric measures. Additional detailed study of bright galactic Cepheids can test the power of models to account for abundance effects.

Evolved Stars and Planetary Nebulae – In the case of evolved stars, measurements have been made of apparent size, T_{eff}, limb darkening, sphericity – and almost nothing has turned out to be simple – it may be debated whether this is unexpected, but the studies are rich in information. Studies of Mira stars can probe through the deep atmosphere and show that the stellar surface is of order $2\times$ smaller than the apparent size of the star, hence the T_{eff} higher than formerly believed (Perrin *et al.*, A&A 436, 317; Ohnaka *et al.*, Astron. ApJ 466, 1099), immediately settling the question of the vibration mode (fundamental). Interferometric studies probe directly the molecular envelope from the surface through the regions of grain formation (Ireland *et al.*, MNRAS 361, 337) to the maser region (Wittkowski *et al.*, Astron. ApJ 470, 191). The mass loss of these stars is asymmetric (Weiner *et al.*, ApJ 636, 1067; Ragland *et al.*, ApJ 652, 650), perhaps linking the irregularities in the stellar envelope (Lacour[iii]), to the shape formation of the PN which they will become. In PN precursors, circumbinary disks have been found in AGB stars (Deroo *et al.*, A&A 474, L45), and dust has been found in a disk perpendicular to bipolar lobes (Chesneau *et al.*, A&A 473, L29), strengthening the association.

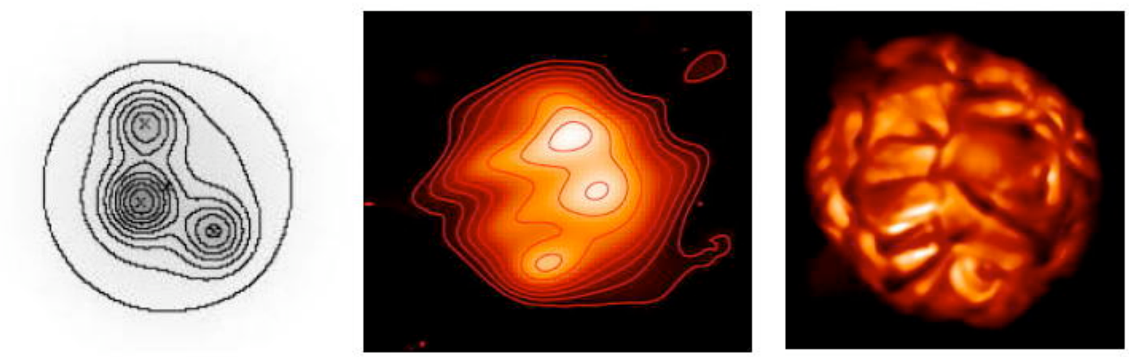

Figure 3. α Ori, M supergiant. (left) The first telescope array image, using a parametric model (Young et al. MNRAS,315, 635) from measurements at 700 nm. (middle) The first array image based on MEM reconstruction (Lacour[ii], 2007) at 1.6 microns (showing the effects of limited UV sampling). (right) A synthetic image based on 3-d hydrodynamic models, showing the appearance of convection (Freytag[iv]) in integrated light.

Supergiants are found to have grain grain formation (perhaps of Al_2O_3) in the atmosphere (Verhoelst *et al.*, A&A 447, 311), and to lose mass (Perrin *et al.*, A&A 474, 599) irregularly in time and space (Tatebe *et al.*, ApJ 670, L21). The mysterious clouds in RCrB have been detected in emitted light (Leao *et al.*, A&A 466, L1), the mystery of stars with both silicate and carbon rich dust has been explained with the detection of silicate dust in companion-associated reservoirs (Ohnaka *et al.*, A&A 490, 173). While interferometry is naturally employed for study of nearby objects, it has served to characterize stars in the Galactic Center, and even the LMC (Pott *et al.*, A&A 480, 115, and A&A 487, 413; Ohnaka *et al.*, A&A 490, 173).

Binary and Multiple stars – Not surprisingly, interferometry excels at delivering precision astrometry for binary orbits, with achievement of measures accurate to 20 microarcsec – by several methods, with more and better in development. These can lead to very accurate masses (some errors <1%, Zhao *et al.*, ApJ 659, 626), distances (improving on Hipparcos, for example, North *et al.*, on. Not. R. Astron. Soc. 377, 415), and to discriminating tests of stellar evolution (Kellerer *et al.*, A&A 469, 633).

It is found that dust disks may be circumstellar or circumbinary (Deroo *et al.*, A&A 450, 181 and A&A 467, 1093), a star filling its Roche lobe has been measured (Verhoelst *et al.*, A&A 470, L21), and mass transfer between stars can be imaged through the orbit (Zhao *et al.*, ApJ 684, L95).

Classic questions in multiple star astronomy concern the distribution of angular momentum, and information on coplanarity of orbits is beginning to accumulate (Muterspaugh *et al.*, A&A 446, 723, ApJ 636, 1020 and AJ 135, 766; Lane *et al.*, ApJ 669, 1209).

Novae and Supernovae – it was expected that high resolution measurements of novae could support distance determinations (from spectroscopic expansion velocity) and this has been achieved. Almost everything else measured is unexpected. Two sources appear asymmetric (Monnier *et al.*, ApJ 647, L127; Lane *et al.*, 669, 1150) and another shows a double shell (Chesneau *et al.*, A&A 487, 223). RS Oph, as a candidate pre-SN1a, is particularly interesting because of the complexity arising from asymmetric explosion (Rupen et al. 2008) and because the appearance of the nova was very different in the emission lines(Chesneau et al., A&A 464, 119) compared to the continuum ((Monnier *et al.*, ApJ 647, L127; Lane *et al.*, 669, 1150)). This object re-emphasizes the need for better "snapshot" uv-coverage for imaging asymmetric and time-changing objects, and the need for simultaneous spectroscopy.

Active Galactic Nuclei – A variety of first measurements of bright AGN are now available in near- and mid-IR wavelengths. Typical sizes of the infrared compact core, assumed to be the torus, have been measured in every case, except for Cen A, which has a thin, dusty disk, the axis of which is aligned with the radio jet (Meisenheimer *et al.*, A&A 471, 453). Measurements of other sources suggest various interpretations. NGC 3783 and the Circinnus galaxy appear clumpy (Beckert *et al.*, A&A 486, L17; Tristram *et al.*, A&A 474, 837), NGC 1069 may have a torus and funnel structure (Rabam *et al.*, MNRAS 2009 in press). NGC 1068 can be accounted for by a double layer spherical distribution (Poncelet *et al.*, A&A 450, 483). As faint-source capability is just coming on line, future measurements can be expected to add image detail and additional targets.

Our and Other Planetary Systems – Interferometry has recently been used to measure the size and shape of the asteroid (234) Barbara (Delbo *et al.*, ApJ in press), and hundreds of other main belt asteroids can be similarly studied for size and multiplicity, leading to albedo and density. From a first observation, 234 is either binary or peanut shaped. This result would have seemed fantastic a few years ago, but now is perhaps not surprising.

Interestingly, for transiting exoplanets, the greatest uncertainty in the diameter (hence the density) of the planet is set by our knowledge of the stellar size. Interferometry with astrometry can reduce this uncertainty by an order of magnitude (Baines *et al.*, ApJ 661, L195-L198 (2007). Interferometric techniques for high dynamic range detection are closing in on the regime of hot Jupiters (Zhao *et al.* in IAU Symposium 249, 71).

5. U.S. Position on the International Scene

The U.S. community 'led' in development and demonstration of optical interferometry through the 1990-2000 decade. This effort culminated in the implementation of 6 substantial interferometric facilities in operation or development. The Infrared Spatial Interferometer (ISI), the Navy Prototype Optical Interferometer (NPOI), the Center for High Angular Resolution Astronomy (CHARA) Array, the Prototype Testbed Interferometer (PTI), and the Magdalena Ridge Observatory Interferometer (MRO, first light 2010) are stand-alone facilities dedicated to full time operation in interferometry. The Keck Observatory, and the Large Binocular Telescope (LBT) are major facilities that support significant interferometric operational modes. (Additional technical and accessibility information will be provided in a proposal to Astro2010.)

Beginning in 2003, when the VLTI, and later its auxiliary array, came on-line, ESO has benefited from a major advantage in capital investment and operations support for interferometry. However, optical interferometry has many instrument parameters. At present, U.S. facilities have an advantage in: number and variety of facilities and beam combination strategies; number of telescopes in arrays (CHARA, NPOI); limiting sensitivity (Keck); nulling capability (Keck, LBT); wavelength coverage (visible – CHARA, and mid-IR – Keck); baseline length (CHARA); and number of beams mixed simultaneously (CHARA, NPOI). The U.S. facilities also have an advantage in accessibility for technical innovation, to an extent that some scientists from ESO member countries have brought their expertise and their beam combiner systems to our shores.

6. Interferometry in the Future

Only 2-telescope measurements have been used in most of the work described above, providing a single baseline per measurement and no closure phase. Existing arrays are already operating beam combiners of 3, 4 and 6 beams, of which the latter, for example, provides simultaneously 15 UV-points and 20 closure phases at each wavelength in the dispersed spectrum. Operation of interferometers in imaging mode is just beginning, and measurements reported to date, cursorily described above, are no more than suggestive of the potential.

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[i] *Decade of Discovery in Astronomy and Astrophysics*, National Academies Press, 1991.
[ii] M. Harwit, *Cosmic Discoveries, The Search, Scope and Heritage of Astronomy*, Basic Books, NY (1981).
[iii] S. Lacour, *Imagerie des étoiles évoluées par interoférométrie*, Doctoral thesis, Paris VI (2007).
[iv] In *The Future of Cool Star Astrophysics* (Univ Colo), 1024, 2003.