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SCIENCE OBJECTIVES FOR GROUND- AND SPACE-BASED
OPTICAL/IR INTERFEROMETRY

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Abstract

Ground-based interferometry will make spectacular strides in the next decades. However, it will always be limited by the turbulence of the terrestrial atmosphere. Some of the most exciting and subtle problems may only be addressed from a stable platform above the atmosphere. The lunar surface offers such a platform, nearly ideal in many respects. Once built, such a telescope array will not only resolve key fundamental problems, but will revolutionize virtually every topic in observational astronomy. Estimates of the possible performance of lunar and ground-based interferometers of the 21st century shows that the lunar interferometer reaches the faintest sources of all wavelengths, but has the most significant advantage in the infrared.

Introduction

For decades astronomers have viewed optical interferometry as the esoteric province of a coterie of off-beat experimentalists, bent mostly on the pursuit of the elusive stellar angular diameter.

But recently, spectacular success in the radio community and rapid technical advances in electro-optics, have stimulated a growing community of scientists committed to the systematic application of interferometry to optical astronomy. As a result of the growing excitement in that community, and real evidence of progress, more than a dozen major facilities for optical/IR interferometry are now in progress, including the largest ground-based telescope project of all time, the VLT.

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We may expect that the still accumulating momentum of these efforts will eventually overcome the cultural obstacle of inadequate funding. The limitations of the terrestrial atmosphere, however, may prove intractable. Unfortunately, some important problems may remain beyond the reach of ground-based interferometry. For these problems, it will be necessary to move to space.

Science Drivers

Increased spatial resolution will further our understanding of virtually any astronomical object to which it is applied. But when the telescope under consideration represents a very large investment, many of the day-to-day issues in astronomy may appear anemic indeed. For example, while I am very interested in the subject of mass loss from cool stars, I would not suggest it as a strong motivation for a billion-dollar investment. To justify a large increment in funding, astronomers historically turn to the issues with deepest philosophical significance - the origin and fate of the cosmos, and man's place in it.

The following specific observational objectives have been selected from contemporary research as examples of the use of optical interferometry for research into the grandest questions. Of course, the list is not in any sense comprehensive. However, it does provide a starting point, and defines an interesting set of performance specifications.

Primeval Galaxies and Galaxy Formation

It is probably safe to assume that the search for primeval galaxies will eventually succeed. Flux distributions and spectra will reveal some information about the stellar and nebular content of these galaxies. Spatial and spatio-spectral information would be invaluable. Searches conducted to date suggest that these objects may have magnitudes $V > 25$ and $K > 20$. The angular diameters are predicted to be ≈ 1 , so resolution of the disk will be possible with a moderate telescope aperture. Interferometry will be useful in obtaining direct measurements of the size of giant star-forming regions, of nuclear accretion disks, etc. Amazingly enough, such measures are not out of the question.

Quasars and the Mass Distribution of the Universe

The discovery of gravitational lensing of quasars by intervening material revealed a new tool for observational cosmology. The currently observed structure in the lensed images, on the order of an arcsec, is apparently induced by galaxy scale masses. Smaller masses are predicted to produce smaller structures. For example, a hypothetical unobserved population of 1 solar mass objects would be revealed by image splitting of order 1 microarcsec (Rees 1981). While the probability of such a population may be low, the alternative methods for direct detection are few. A good selection of quasars may be reached with a limiting magnitude of ≈ 22 . Rix and Hogan (1988) have already reported a correlation of apparent quasar brightness with respect to proximity of foreground galaxies to the line-of-sight, suggestive that microlensing is in fact occurring, although this interpretation is not unique (Narayan 1989).

The Structure of Active Galactic Nuclei

The longstanding problem of energy generation in Active Galactic Nuclei (AGN) may be subject to direct study with high spatial and moderate spectral resolution. Ulrich (1988) has described the possible observational objectives available to interferometric study. At 10 milliarcsec, it is possible to study the distribution of ionized gas (the narrow line region). With resolution approaching 100 microarcsec, it should be possible to resolve the broad line region and a possible accretion disk. With microarcsec resolution, it should be possible to resolve the hypothetical UV continuum photosphere. Relatively bright AGNs are known, but to have a reasonable set with minimal extinction and appropriate viewing angles, it may be necessary to reach $V=20$.

The Scale of the Universe

Precision astrometry will have profound implications for many areas of astronomy. With microarcsec precision, the distances to the nearest galaxies could be determined directly with a precision of 1 percent (Reasenberg et al. 1988). Measurement of these distances would confirm and secure basic stepping-stones to the cosmological distance scale. The brightest stars in M31 have magnitudes $V \leq 17$.

Galactic Structure

Astrometry, again, is the key to a more comprehensive study of structure and dynamics of the galaxy and its nearest neighbors. Microarcsec precision will permit 3-D mapping of our entire galaxy (in the infrared, to penetrate extinction in the disk) and the Magellanic clouds. Such information will greatly strengthen our understanding of the current state of the galaxy and its evolution. Typical giant type stars (K0III) in the Magellanic clouds have magnitudes $V \approx 19$ or $K \approx 16.7$.

Planet Formation

An observational probe into the origin of our solar system may be available from observation of young stars in star-forming regions. At typical distances of such regions (500 pc) a solar type star will have an apparent magnitude of 13. The radius of the Earth's orbit at the same distance will subtend an angle of 2 milliarcsec.

Seeing limited and speckle measurements of T Tauri stars have in a few cases revealed possible preplanetary material with possible disk-like structure, and angular extent of order 1 arcsec. Planetary formation may occur within such disks, and although direct observation of the formation process may be obscured, direct detection of the radial distribution of abundances in the preplanetary disk may be possible.

The Nearest Stars

The nearest stars are interesting primarily for their proximity. To the astronomer this promises the opportunity for detailed study. To the dreamer, they are stars that our descendants might hope to visit in a lifetime with Earth-scale technology and without violating physical laws. The nearest 100 stars have magnitudes $V \leq 13$, and are at distances up to approximately 6.5 pc (Allen 1973). The apparent angular diameter of the sun at 5 pc would be 1 milliarcsec. Direct observation of the sunspot cycle might require spatial resolution of 10 microarcsec.

Summary of Instrumental Requirements

Table 1 collects the estimates of required sensitivity and spatial resolution for the scientific objectives described above. Of course it is understood that in many cases the requirements are merely order-of-magnitude estimates.

Table I. Instrument Requirements for Science Objectives

Program	V mag	K mag	Resolution (microarcsec)	Precision (microarcsec)
Primeval galaxies	>25	>20	?	
Quasar lensing	20		1	
Active Galactic Nuclei	20	18	1-100	
Distance scale	17			1
Galactic structure	19	17		1
Cosmogony	13	15	1000	
Nearest stars	13	13	10	

The range of the requirements is clearly quite diverse, and with the inclusion of a wider range of scientific objectives (Ridgway 1989) would be more diverse still. It appears that except for primeval galaxies, still a speculative subject, the magnitude limit does not appear to be extreme. However, when details of image complexity and dynamic range are folded into the estimates, the effective sensitivity required will in some cases be much fainter than the numbers tabulated here.

The principal regimes of spatial resolution are of order 1 milliarcsec and of order 1 microarcsec. The optical baselines required to reach these regimes are shown in table 2. Obviously, microarcsec resolution is more likely to be achieved at short wavelengths.

Table 2. Baseline Required for Angular Resolution

Wavelength (microns)	1 milliarcsec resolution	1 microarcsec resolution
0.55	0.11 km	11. km
2.2	0.45	45.
10.0	2.0	200.

Now let us review the potential of interferometry from the ground and from low Earth orbit, to see what performance might be accomplished by aggressive development programs without the cost of a lunar-based telescope.

The Promise of Ground-Based and Near-Earth-Orbit Interferometry

Ground-Based Interferometry. The Earth probably offers at least a few adequate observing sites with the required features for a large optical interferometer: good seeing, large baseline potential, stable subsoil, and seismic quiescence. The essential problem in ground-based interferometry is overcoming the wavefront perturbations introduced by the atmosphere, and the vibrations in the instrument provoked by wind. Since we are looking into the future, we will adopt a telescope configuration which might be appropriate for the early years of the next century. We assume that our interferometer consists of two or more 8-m telescopes, located on a site with seeing of 1 arcsec at 5000\AA .

For bright sources, the source itself will provide sufficient information to measure and compensate the atmospheric errors. Roddier and Lena (1984 a,b) give relatively conservative estimates for the limiting magnitudes for source referenced phase stabilization, and find, e.g., $V \approx 13$, $K \approx 14$, and $N \approx 5$.

If the technique of an artificial reference is incorporated, then each telescope may be equipped with a laser reference star system. The artificial star will be generated in the ionosphere and used to control an adaptive optical element which corrects the wavefront distortions, effectively increasing the r_0 parameter to a value comparable to the telescope pupil diameter. Thus each 8-m aperture will be fully phase coherent.

However, the laser reference star system provides no help with the relative phasing of separate telescopes. The relative phase of the two telescopes will still drift with a time constant characteristic of the atmospheric turbulence or of the instrument vibrations. The cophasing of independent telescopes still requires reference to a source in the field. An estimate of the characteristic time for relative phase drift can be obtained from the ratio of the phased beam diameter to the wind velocity in the relevant part of the atmosphere. For an 8-m aperture and 4 m/sec wind, the phasing will likely drift in times of order 2 sec. To preserve phasing there must be a source in the field bright enough to obtain reasonable signal-to-noise ratio (SNR) in 2 sec.

Optimistic estimates for the limiting magnitudes with an 8-m ground-based (BG) telescope, using an artificial reference, are shown in table 3.

Owing to the assumed large aperture of the telescope, the ground-based interferometer will very quickly obtain high SNR on any source bright enough for cophasing of the telescopes.

For sources too faint for cophasing, the ground-based telescope must be used in an absolute mode, whereby the coherence condition between the telescopes is obtained by reference to the instrument. With this method it will only be possible to gain a few magnitudes in sensitivity, and at the price of long observation times. Furthermore, the method of absolute interferometry may not be useful with large telescopes, as it may not be possible to obtain the internal metrology required for a large and necessarily flexible structure. Thus the optimistic sensitivity estimate for the artificially-referenced 8-m telescope may represent an ultimate performance limit for ground-based interferometry.

It is difficult to estimate the maximum baselines which may be obtainable on the ground. Baselines of order 100 m will clearly be no problem. The Sidney University Stellar Interferometer, currently under construction, has baselines to 640 m. Multikilometer baselines appear possible, although the practical problems accrue steadily. For example, it may not be possible to find a site which offers a multikilometer baseline, adequate UV plane coverage, good seeing, and acceptable meteorology.

Near-Earth Orbit

Installing an interferometer in space has obvious advantages in escaping the effects of the atmosphere. The potential improved performance of an instrument in space may be described, following Greenaway (1987): Greenaway, A.H. 1987 in ESA Workshop on Optical Interferometer in Space, ed.n. Longdon and V. David, (ESA, Noordwijk), p.5.

$$\frac{SNR (space)}{SNR (ground)} \approx \left(\frac{d_s}{d_g}\right)^n \left(\frac{t_s}{t_g}\right)^{n/2}$$

where d is the area of the coherent aperture and t the coherence time on ground and in space. The coefficient n will be typically 1 or 2, depending on the limiting noise source. As we have seen, with the use of artificial reference stars, the ratio of coherent aperture areas may greatly favor the

ground (8-m telescopes). This ground-based advantage may be most easily realized in the near infrared, 1 to 3 μm , where the atmospheric turbulence is low and the thermal background is still modest. Potentially, the factor t favors space, where no atmospheric effects enter. Is this gain actually realized?

While moving to Earth orbit eliminates the problems of the atmosphere, it also deprives the experiment of a massive, rigid foundation that can absorb vibrations with minimal deformation. The use of self-referencing to phase an instrument is conceptually similar in space to on the ground. In space, the limiting magnitude may be brighter owing to the smaller coherent aperture. However, the isoplanatic region may be very large because of the absence of atmosphere. Instrument deformations induced by gravity gradients should be slow, but may have large amplitude for large structures, hence are another hindrance to large baselines in near-Earth orbit. Therefore, baselines exceeding 10-100 m would appear questionable for near-Earth orbit. It is probable that in near-Earth orbit the most interesting interferometric configurations will employ relatively short baselines, permitting excellent structural rigidity and control.

A number of extensive studies for orbiting interferometers have been completed, and are a good basis for projecting the probable performance of such a system. A type of instrument which appears very promising is a compact system, such as POINTS (Precision Optical INTerferometry in Space; Reasenberg et al. 1988), and the extension of the concept to somewhat larger configurations and larger numbers of telescopes. POINTS employs a two-telescope interferometer (actually two such at right angles) with 25-cm apertures, to reach a projected limiting magnitude of $V=17$. This limit compares favorably to the limit estimated above for a ground-based 8 m, probably because of the relative long coherent integration times expected with POINTS. With a small (2-m) baseline, POINTS achieves microarcsec precision in astrometry by careful control of errors rather than large optical baseline. This appears to be an excellent strategy for near-Earth orbit.

Reaching much fainter limiting magnitudes would require larger telescopes or longer integration times. This would aggravate the structural and control problems. Thus, there may be natural limits to the sensitivity of near-Earth orbit interferometric telescopes.

The tradeoffs between high Earth orbit and the lunar surface deserve careful study, and the preferred location may depend on the assumptions concerning transport cost and accessibility.

A Lunar Interferometric Array

Concepts for a lunar optical/IR interferometric array are discussed in detail in the other contributions in this volume. Here I will just make some predictions of the sensitivity of a lunar array.

Compared to ground and near-Earth orbit instruments, the lunar-based array is likely to gain primarily in the allowed coherent integration time. Times of an hour appear reasonable, and that is the value used here. In fact, guaranteeing a large value of this order appears to be the critical technical issue for the scientific success of the lunar-based array, hence deserves the most careful scrutiny.

Limiting Sensitivity

With a coherent integration time of an hour, a lunar telescope will naturally reach impressive limiting magnitudes. Estimates for the magnitude limits for a 1.5-m lunar-based telescope (LB), are shown in table 3 for one set of assumptions.

Table 3 Limiting Magnitudes for Cophasing of Telescopes*

Wavelength (microns)	0.55	2.2	3.5	5	10
8.0 m BG - Artificial reference	28	21	17	14	10
1.5 m LB - Source reference	29	25	24	19	13

*Efficiency 0.1, integration time 3600 sec, S/N=5, point source reference (visibility = 1.0); additional parameters for the IR: warm emissivity 0.20, cold efficiency 0.13, telescope temperature 150K; detector read noise 30 e⁻, detector dark current 1 e⁻/sec, noise from four pixels contributes to every fringe detection. It is assumed that all the photons in a bandpass $\delta\lambda/\Delta\lambda=0.5$ are utilized.

The relative performance of the telescopes depends on the limiting noise source. In the visible, the limit is source photon noise for short integrations, and sky background for longer integrations. In the near-infrared the detector noise is the limit, and in the longer wavelengths the telescope emission.

The limits in table 3 are impressive. However, they are also misleading. For ground-based observations with a large telescope, the major problem was phase stabilization for any object for which that could be maintained in SNR would accumulate to a high value within minutes. In the lunar case, with an assumed small telescope aperture, phase stabilization can be achieved for faint sources, but only with long integrations. Thus table 3 is useful for estimating the limiting magnitudes for very high priority faint sources. As the faint limit, for the lunar-based case, low signal would probably preclude mapping, and only estimation of typical source size and other basic parameters might be possible.

A more realistic limiting sensitivity for image reconstruction would be to require a SNR of 100 (or even much higher) in 1 hour. These limits will be found in table 4. The values for the ground-based telescopes are simply copied from table 3 because the faint limit in that case is set by the limitations for phase stabilization.

Table 4. Sensitivity Limits for SNR = 100 in 1 Hour

Wavelength (microns)	0.55	2.2	3.5	5	10
8.0 m BG - Artificial reference	28	21	17	14	10
1.5 m LB - Source reference	26	22	21	16	9

Note that the values tabulated are for a broad spectral band ($R=2$) and for a single baseline, appropriate for an object with approximately one "pixel." Study of a source with N pixels will require typically N baselines, and total integration time increased by N^n , where n will depend on the beam combination strategy and the limiting noise, but typical values in practice will be around $n=1$. Assuming that we can always achieve $n=1$, then for a source at the limiting sensitivity a total observation time of order 100 hours will be required for a source with 100 image pixels.

On the positive side, fringe detection may be carried out (in either the pupil plane or the image plane) to preserve the spectral information at moderate resolution while stabilizing the fringes with the broadband flux, so some spectral resolution is implied at even the faint source limit.

The table of limiting sensitivities shows the well known strong dependence of IR sensitivity on telescope temperature. The dependence on temperature is so much stronger than the

dependence on telescope size that a cooled telescope will almost always win. At the temperature selected for this discussion, $T=150\text{K}$, the background on the blue side of the Planck distribution is greatly reduced, giving greatly improved performance at $2\text{-}5\ \mu\text{m}$. To extend this improvement to $10\ \mu\text{m}$ would require a telescope temperature of about 65K , hence probably a specialized, rather than general-purpose, instrument.

Intercomparison of the Ground and Lunar Interferometers

In this comparison, both telescopes perform quite well (even spectacularly). The space instrument has a clear sensitivity advantage at the faint source limit. This advantage is largest in the infrared. However, this conclusion is obviously dependent on the numerous parameters — especially the coherent integration time on the lunar surface and the telescope temperature. Assumed diameters of interferometric telescopes on the ground and the Moon may be overly optimistic, and adaptive phasing of ground-based telescopes may not work as assumed.

A major shortcoming of this simple comparison of photon rates is the issue of the dynamic range achievable through the terrestrial atmosphere. It seems to me possible that correcting the atmospheric corrugations on a scale of r_0 may never suffice to reach really high quality imagery, even with closure techniques. But this will only be known as a result of trying.

It is certain that the first major step toward a lunar-based interferometer with many telescopes will be a ground-based interferometer with a few telescopes.

Conclusions

A lunar-based telescope has obvious advantages in the spectral ranges that are not available from the ground, and this should be an important consideration in developing a lunar observatory.

A general-purpose array will not satisfy both short wavelength and thermal IR requirements, so a separate thermal IR array might be considered.

Precision astrometry probably does not require either the lunar surface or the very large baselines available on the Moon.

A lunar-based interferometer will be competitive in its ultimate sensitivity limit with large ground-based telescopes. In the baseline model discussed here, the lunar-based interferometer will be capable of studying sources 1 to 7 magnitudes fainter in the region 0.3 to 10 μm . For sources bright enough to study from the ground, high SNR may (formally) be achieved more quickly from the ground than from the Moon. However, the realizability of this ground-based performance may be difficult or impossible to obtain in practice.

The lunar interferometer will excel in precision imaging of relatively bright sources (e. g., $V \approx 26$ and $K \approx 25$). This covers all of the scientific problems discussed above and summarized in table 1. It will also have superb limiting sensitivity, applicable to mapping of sources so faint their existence is not yet even suspected.

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PART IV

LUNAR INTERFEROMETRIC ARRAYS

Politics, history, philosophy, geology, and technology are all part of the papers in Part IV that describe various aspects of constructing LOUISA on the lunar surface. These papers, derived from talks presented at the workshop, provide the foundation upon which the working groups were able to build a straw-man design for LOUISA.

C.B. Pilcher presented a very informative and entertaining after-dinner talk at the workshop on political forces that have driven space exploration in the past and may strongly influence a decision to build a lunar base; a paper derived from this talk leads off this section. N. Woolf waxes philosophical in discussing basic questions concerning human goals, the space program, and special science issues for a lunar optical interferometer. S.W. Johnson follows with an interesting review of past design studies of lunar-based astronomical telescopes, providing an important historical perspective. G.J. Taylor describes the lunar environment in detail with particular emphasis on both the advantages and concerns regarding the Moon's geologic features that will influence the operation of LOUISA. Johnson *et al.* then describes possible lunar environmental effects on an optical interferometer. B.F. Burke reviews and updates his original pioneering proposal for an optical VLA on the Moon including a discussion of the sensitivity, array configuration, optics, and costs; in an appendix, Burke also describes the limits on heterodyne receivers for optical interferometers. S.W. Johnson and J.P. Wetzel end Part IV with a discussion of required technologies for LOUISA.