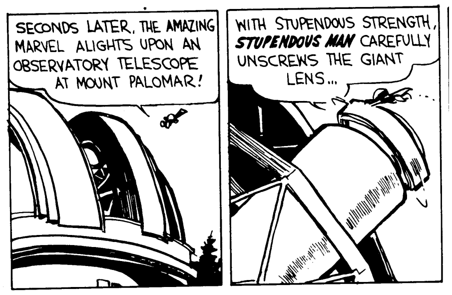
1. High Resolution Imaging



Outline

This chapter examines why high spatial resolution images are important to astronomy, the reasons why the resolution of conventional telescopes is limited, and some solutions to these problems.

1.1 Introduction

The Cambridge Optical Aperture Synthesis Telescope (COAST) was built to use radio astronomy techniques to produce high resolution visible images of astronomical objects. Although COAST was designed as a visible instrument, there are a number of astronomical and technical reasons why it should perform better in the near infrared. This project was to modify COAST to operate in the near infrared.

1.2 Why high resolution?

Astronomy is unique among physical sciences in that it is not possible to perform direct experiments. Since we can only observe phenomena, the quality of the observations is of great importance. One of the main problems in astronomical observations is the limited spatial resolution of images taken through the atmosphere. The astrophysics of many fundamental astrophysical processes such as star formation, late stages of stellar evolution, binary systems and active galactic nuclei can be examined only with models that are based on indirect measurements of the conditions in these systems. Detailed images showing what is actually happening in these systems are an important way of determining which, if any, of these models are at all realistic. The range of possible targets for the instrument built for this project is described in section 1.6 and Ridgway(1988).

1.3 Why is it difficult?

The smallest details which can be resolved in an image produced by a telescope are limited by both the size of the telescope and the effects of the atmosphere. The angular resolution of a telescope is proportional to the diameter of the aperture and inversely proportional to the observing wavelength. An eye with an aperture of approximately 5 mm can only see detail in objects on scales larger than about 20 arc-seconds. An early telescope increased the aperture to around 100 mm which could reach scales of 1 arc-second. This increase in resolution allowed the moons of Jupiter to be seen for the first time but was still too small to resolve stars which remained as dots. The size of telescopes has increased enormously over the last century and this, together with the sensitivity of modern detectors, means that much fainter objects are now detectable. However, the detail that these instruments can resolve in an astronomical source has hardly increased at all since the invention of the telescope.

Any telescope on Earth must look at the stars through many kilometres of turbulent atmosphere that forms a constantly changing lens across the aperture of the instrument through which light from the object must pass. The effect of this is that even on the best astronomical site, an optically perfect telescope would produce images with details of only 0.5 - 1 arc-seconds. This is only a few percent of the theoretical maximum resolution. To provide images of astronomical objects with enough detail to answer many astrophysical questions, resolutions a hundred times better than this are needed.

An obvious solution to the problem of atmospheric degradation of the image is to put the telescope above the atmosphere. Unfortunately apart from the enormous cost of building, launching and operating space based telescopes, the practicalities of putting them into orbit means that an instrument such as the Hubble Space Telescope (HST) has a mirror only 1/4 the diameter of the largest ground based instruments. Even though free of atmospheric image degradation, the telescope is limited by diffraction to a resolution of around 50 milli-arcseconds (mas).

An increasingly common solution to the image resolution problem for ground based telescopes is the use of adaptive optics. In this technique an element of the optical chain is adjusted in real time to counter the effects of the atmosphere. The usual scheme is for actuators on the back of a thin mirror to bend it into a new shape to cancel the wavefront distortions introduced by the atmosphere. The shape required is calculated by observing the degraded image of a nearby point source. Unfortunately there a number of practical difficulties which make adaptive optics systems impracticable under most circumstances. The large size of modern telescope apertures compared to the scale on which atmospheric turbulence distorts the wavefront means that a large number of degrees of freedom are needed. This implies that many photons need to be recorded to sufficiently analyse the wavefront and this measurement must be made quickly so that the atmosphere does not change before the correction can be applied. The point source calibration object must be within a small angular distance from the target so that the light from it passes through a similar layer of atmosphere. This means that observations are limited to those few astronomically interesting objects which are close to very bright point sources. Even if adaptive optics systems could be perfected and the effects of the atmosphere totally removed, the current generation of 8-10 metre instruments are probably the largest telescopes that can be made from a single mirror. The diffraction limit of these telescopes still reduces the resolution to much less than that needed for many astrophysical programs. Instead we must use less direct imaging techniques.

1.4 Interferometry

The most practical technique for measuring high resolution information in astronomical objects is interferometry. This relies on the van Cittert-Zernike theorem which states that (for a source at infinity) the spatial coherence of light received at two separate points is related by a Fourier transform to the brightness distribution of the source, Goodman(1985).

In optical astronomy this idea can be used to build an instrument where light from two separated apertures can be combined by a lens to produce an image of the source. This image will be crossed by light and dark fringes where light from the two apertures interfere. The coherence of the light can be simply measured from the contrast, or visibility, of these fringes. For reviews of interferometry in visible imaging see Readhead(1988) and Roddier(1988).

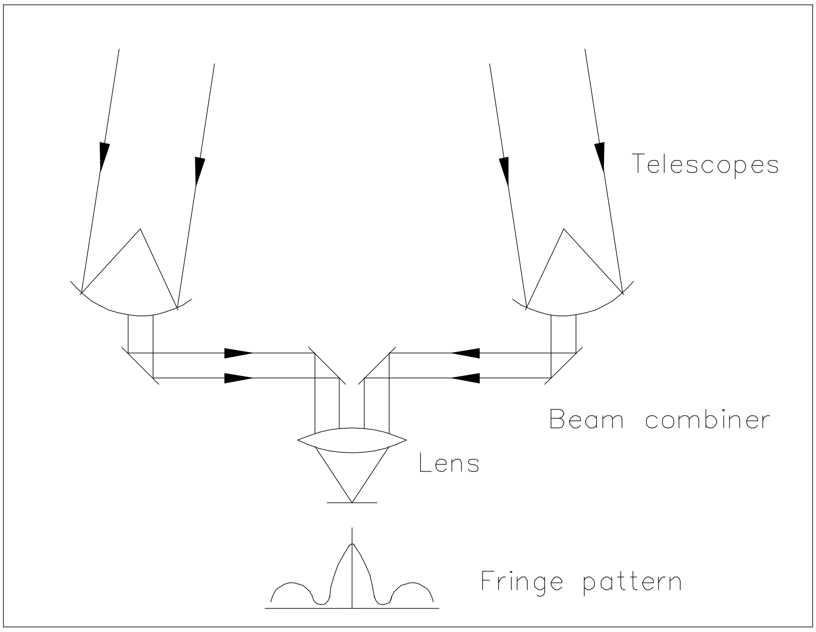


Figure 1.1: A two element interferometer

The application of this technique to astronomical imaging was suggested by Fizeau in 1868 Fizeau(1868) and an experiment, measuring the diameters of the moons of Jupiter, was carried out by Michelson in 1891 using a mask with two holes placed over the aperture of a large telescope, Michelson(1891). The first practical example of stellar interferometry had to wait until 1921 when Michelson built a 20 foot interferometer using two mirrors on a beam mounted across the top of the 100 inch Mount Wilson telescope. This instrument measured the diameters of six stars, Michelson(1921). To do this the observer had to estimate by eye the visibility of fringes crossing the faint image of a star, which were constantly moving due to the atmosphere and the telescope structure bending. The limitations of this measurement meant that optical interferometry was stalled for half a century until a way of automatically measuring fringe visibilities could be found, Tango(1980).

The much longer wavelengths of radio astronomy means that it is impossible to build a single radio telescope large enough to have a resolution comparable to an optical telescope. The easiest way to produce higher resolution was the use of interferometry. By building arrays of widely separated small telescopes, an instrument could be synthesised which had the same resolution as a single aperture the size of the largest separation. Initially the separations of the telescopes were small enough that differences in the radio transmission of the atmosphere between individual antennae were negligible. However as interferometers were stretched to intercontinental distances, the atmosphere introduced significant differences between the signal received at the component telescopes. Radio astronomers now had to correct for the effects of seeing, analogous to that in the visible. Since radio telescopes are small compared to the size of atmospheric disturbances, the phase across a single dish is generally uncorrupted. This property led radio astronomers to realise that the phase error due to the atmosphere above each antenna could be assigned to a single term from just that antennae. If there are many antennae observing the source simultaneously then, although the phase for each antenna is corrupted it is possible to recover some error free quantities about the relative phase between antennae. The usual application of this is the *closure phase* where the visibility phase is summed around a triangle of three telescopes. For details of the application of closure phase to optical imaging, see Cornwell(1989) and Haniff(1988).

A further complexity arises since the aperture synthesised by the array of telescopes is not completely filled, and so directly Fourier transforming the visibility measurements does not produce the best image. Instead, a range of statistical and iterative techniques have been developed by radio astronomers to produce a map from this data. Although the visibility measurements are less corrupted by the atmosphere than the phase, they alone do not provide enough information to produce a reliable map. The closure phases provide an extra constraint which is useful in producing a realistic image. These techniques although developed for radio astronomy, are directly applicable to a special type of optical telescope. For details of the image reconstruction techniques see Perley(1989).

Returning to optical astronomy, the high resolutions achievable by aperture synthesis and the correction of atmospheric degradation by closure phase, make the idea of building an optical analogue of a radio telescope seem an ideal solution. An instrument called the Cambridge Optical Aperture Synthesis Telescope (COAST) was built by the Mullard Radio Astronomy Observatory at Cambridge to demonstrate that this is possible, Baldwin(1988).

The detailed design and construction of COAST and its modifications to operate in the infrared will be described in a later chapter. The general form of COAST is quite simple. The instrument is made up of four individual telescopes, each small enough that the atmosphere across a single aperture does not greatly affect the image. The light from each telescope is steered back to a central optics lab by mirrors. A system of relay mirrors on moving trolleys correct for the path length difference between different optical paths through the instrument. The beams from each telescope are interfered to produce a fringe pattern. The visibilities of the fringes are then measured by a detector.

1.5 Why infrared?

COAST was originally designed to operate at visible wavelengths. This project was to modify the instrument to operate in the near infrared. This has been possible because of the introduction of new detector technology but why was it needed ?

As the atmosphere has such an effect on the performance of telescopes, many theoretical studies have been made to characterise its effects. The most common model allows the atmosphere to be described by two simple parameters which specify the distance and timescale over which the atmosphere acts to degrade an image.

The size of a circular patch across which the atmosphere corrupts the wavefront by one radian is given by Fried's parameter (r_0), Fried(1966). The common models usually assume that the atmospheric turbulence is frozen, and so does not change as it is blown past the telescope. Using these factors, a characteristic timescale, t_0, can be defined from the size of r_0 and the wind speed. At visible wavelengths, in good conditions, these parameters are around 10 cm and 5 milliseconds respectively.

It is these values which determine the operation of an interferometer. In order that the wavefront across a telescope is largely uncorrupted, the aperture must be around r_0 in size. Similarly each measurement of the fringe pattern is typically made in an exposure time less than t_0 so that the fringes are not blurred by the atmosphere. Since these apertures and exposure times are much less than those commonly used in astronomy, interferometers operate in a regime where they are starved of light and so are generally limited to the brightest objects.

Fortunately both these parameters improve with increasing wavelength. The coherence time, and so the exposure time increases as $\lambda^{6/5}$. The size of r_0 also increases as $\lambda^{6/5}$ and so the usable telescope area increases as the square of this. This means that for the same level of atmospheric degradation, both larger telescopes and longer exposures can be used. The light from the astronomical object travels along a different path through the atmosphere to each telescope, this introduces a random path error due to local changes in refractive index. In order to produce high visibility fringes the coherence length must be long enough to allow for these errors, this implies using a narrow bandwidth. Since the coherence length is proportional to wavelength, a larger fractional bandwidth can be used at longer wavelengths. Overall these effects combine to give a theoretical improvement in signal received, for the same phase error, of $\lambda^{4.6}$. In practice these gains may not be realised since longer wavelength detectors may have higher noise and the small size of the existing telescopes will limit the possible increase in received astronomical flux.

The nature of the astronomically interesting objects available to an interferometer also favours the near infrared. Since optical interferometers will always be starved of light, it makes sense to observe interesting objects at the peak of their energy emission. For the near infrared (λ = 1-2.5 µm) this implies objects with a temperature of 1000-3000K, although the signal to noise arguments above suggest that even visible objects may be better observed in the infrared.

1.6 Astronomy

This section reviews some of the possible astronomical objects of interest to optical and near infrared interferometry. The range of targets is limited by the need for bright sources and structure on scale of milli-arcseconds. For further details see Dyck(1986).

1.6.1 Photospheres of cool stars.

Cool late type M and C giant stars are ideal objects for interferometry; they have high red and infrared fluxes and large diameters and because of this they can be observed and resolved at large distances. A survey of type M6 and later shows several hundred stars with a range of sizes from 0.5 to 68 mas brighter than 0 magnitude (at 4.2 µm), Lockwood(1972).

In addition to their abundance, most late type stars have interesting properties. A particular class called Mira variables have regular pulsation cycles of a few months with a change in brightness of several magnitudes. Direct measurements of the diameters of Mira type stars are needed to resolve theoretical questions about the mechanism driving their oscillation. Observations in the infrared are especially important since the extended atmosphere observed in visible wavebands consists of a complex mixture of molecular species that change the optical depth over small changes in observing wavelength. At near infrared wavelength the stars can be observed in the continuum and a much more useful size estimate is possible, Dyck(1987).

1.6.2 Circumstellar material.

Circumstellar material has been a popular target for infrared speckle observations. The sources usually consist of a luminous late type star surrounded by a large dust shell. The combination of high infrared flux and relatively large angular size make them useful objects for a system such as COAST, Christou(1991).

1.6.3 Young stars in molecular clouds.

The nearest star forming region in Taurus is at a distance of about 150 Parsec and so a COAST type interferometer could resolve detail on the scale of an astronomical unit in the near infrared. Another star forming region in Orphiucus is at a similar distance.
The early stages of star formation occur inside dust and gas clouds that are opaque to visible and near infrared light. The star will probably become visible in the near infrared first. Individual stellar disks cannot be resolved at this distance but more important is the detection of multiple systems. Despite the fact that most stars exist as multiple systems, star formation models concentrate on single objects because of a lack of data about the early stages of star condensation. Observations of star forming regions at high resolution while the stars are still inside the dust cloud will answer questions about the formation of multiple systems, Simon(1992).

1.6.4 Quasars

The brightest and nearest active galactic nuclei is 3C273 at a redshift of z=0.158. At a distance of approximately 500 Mpc ($H_0 = 75$), a resolution of 1 milli-arcsecond would resolve features 2.5 pc in size on the object. The broad line region of active galactic nuclei typically reach a few parsecs from the central core. The narrow line region extends up to 1000 pc. Images of 3C273 from the HST show a jet 20 arc-seconds long which is broken into a number of small knots each around 100 mas, Thomson(1993).

Although 3C273 is the brightest AGN, the central region is only $M_v = 13$ and so probably too faint for COAST at visible wavelengths, although near-infrared observations are more promising.

1.7 Conclusion

I have said that high resolution images are important to astronomy, that interferometry is the most practical way of achieving very high resolutions (milli-arcsecond) and that this is best done at near-infrared wavelengths. This chapter has reviewed the basic principles behind the design of COAST. The next chapter will describe the background to the physics and technology of the infrared detectors that make this project possible.