1
Introduction

1.1 Historical introduction

The Earth orbits a star, the Sun, at a distance of 140 million km, and the distance to the next closest star, α-Centauri, is more than $4 \cdot 10^{13}$ km. The Sun is one star in our galaxy, the Milky Way. The Milky Way has 10^{11} stars and the distance from the Sun to its center is $2.5 \cdot 10^{17}$ km; it is one galaxy in a large group of galaxies, called the Local Group and the distance to the next nearest group, called the Virgo Cluster, is about $5 \cdot 10^{20}$ km. The Universe is made up of a vast number of clusters and superclusters, stretching off into the void for enormous distances. How can we learn anything about what's out there, and how can we understand its nature?

We can't expect to learn anything about distant galaxies, black holes or quasars, or even the nearest stars by traveling to them. We can maybe explore our own solar system but, for the foreseeable future, we will learn about the Universe by using telescopes, on the ground and in space.

The principal methods of astronomy are spectroscopy and imaging. Spectroscopy measures the colors of light detected from distant objects. The strengths and wavelengths of spectral features tell us how an object is moving and what is its composition. Imaging tells us what an object looks like. Because distant stars are so faint, the critical characteristic of a telescope used for spectroscopy is its light-gathering power and this is determined principally by its size, or "collecting area." For imaging, the critical characteristic is its resolution. In general, we don't know the distance to the objects we are looking at; we can only measure the angle they subtend at the location of the observer. So we use the term "angular" rather than spatial resolution to characterize the imaging capability of a telescope. In principle, the larger the telescope aperture, the better is its inherent resolution. However, in practice, telescopes operating on the ground, observing through the Earth's turbulent atmosphere, are limited by atmospheric turbulence.

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The inherent or *diffraction-limited* angular resolution limit of a telescope is determined by the ratio λ/D between the wavelength, λ, of the light used for the observation and the diameter, D, of the telescope aperture. A 10-m telescope, like the Keck telescopes on Mauna Kea in Hawaii, has an inherent angular resolution limit of about 10 milli-arcseconds in visible light ($\lambda = 500$ nm). 10 milli-arcseconds is the angle subtended at Earth by a soccer ball on the surface of the Moon. The Earth's atmosphere degrades the resolution so much that the typical resolution is only about 1 arcsecond, which is no better than the inherent resolution of a 10-cm telescope. Even at the site with the best seeing in the world, in the remote mountains on the Antarctic continent, the best seeing is 0.15 arcsecond. Techniques such as adaptive optics and speckle interferometry have been developed for measuring the effects of the atmosphere and correcting them, which improve ground-based resolution to the inherent limit. By putting a telescope in space, the atmospheric disturbance problems can indeed be avoided, so that the inherent diffraction-limited angular resolution of about λ/D can be obtained. However, one recalls the costly design disaster in the early 1990s whereby the 2.4-m Hubble Telescope optics had to be corrected by the addition of the COSTAR system before this could be realized.

The closest star to us, α-Centauri, is actually a triple-star system, and its largest component is a very close analog to our Sun. Its angular diameter is only 7 milli-arcseconds, less than the resolution limit of the largest telescope. The second closest star like our Sun, τ-Ceti, is three times farther away and has an angular diameter only 2.5 milli-arcseconds. Clearly, if we want to study any of these in detail, we need much better angular resolution. In the near future there will not be any telescopes much larger than the Kecks; studies for a 100-m telescope are currently being carried out, but whether anything approaching this size is technically or financially feasible is an open question. Interferometry is the proven approach to obtaining higher resolution without having to build enormous telescopes. In an interferometer, we coherently combine the light from two or more telescopes or apertures. The angular resolution is then given by λ/B, where B is the baseline, or largest edge-to-edge separation between the telescopes. So we can take several small telescopes and separate them by large distances in order to achieve resolution comparable to that of a large telescope with diameter B. Of course, producing images from such an array is more difficult than with a conventional telescope, but it can and has been done.

Stellar interferometry was first suggested by H. Fizeau in 1868. In a report to the French Académie des Sciences on the judgement of the Bordin prize, offered in 1867 for an essay on methods to determine the direction of the vibrations of the aether in polarized light, Fizeau remarked that interference fringes produced from a source of finite dimensions must necessarily be smeared by an amount depending on the size of the source. He suggested that observation of the smearing, or lack

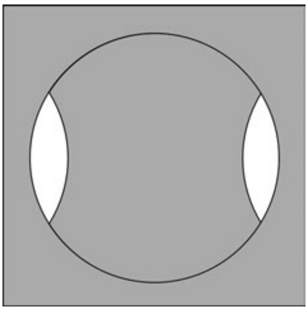

Fig. 1.1. Mask used by Stéphan on the Marseilles telescope. This mask provides a pair of identical apertures with the largest separation possible.

of clarity, of the fringes created by a star through a large telescope whose aperture was masked by a pair of well-separated apertures, could be used to put an upper limit on its angular dimensions. The challenge was taken up by M. Stéphan within a few years. Stéphan was the director of the Marseilles observatory, whose 80-cm reflector was at that time the largest in the world. He masked the aperture in a manner which gave two identical apertures with the largest possible separation (figure 1.1) and indeed observed fringes crossing the now enlarged image of a star. In fact all the stars which he observed eventually showed fringes, from which he deduced an upper limit to their diameter of 0.16 arcsec, which is indeed true (Stéphan 1874). But in doing so, he improved the practical atmospherically limited resolution by almost one order of magnitude.

More than a decade later, A. A. Michelson (1890) came up with the same idea of using a pair of small openings in a mask covering the aperture of a telescope to produce fringes, and thereby to measure the profile of a star. Michelson nowhere refers to the earlier works of Fizeau or Stéphan, and Lawson (1999) has discussed the question of whether the French work was indeed known to Michelson. It would appear that although Michelson had visited Paris in 1881 for an extended study period and may have met Fizeau, there is no evidence of their having discussed this question. Michelson's paper in 1890 not only reinvented the idea of stellar interferometry, but describes in detail how it should be carried out by measuring the fringe visibility, a concept there defined for the first time, as a function of aperture separation. He discusses the expected results not only for uniform disk-like and binary stars, but also for limb-darkened stars, using a model previously developed to describe the intensity profile of the Sun. The technique he used for these calculations was to superpose the interference fringes created from each point on the extended disk of the star. The concept of the coherence function, usually used for such calculations today, arose decades later from the work of F. Zernike in 1938. From the instrumental point of view, Michelson pointed out that for useful measurements of stellar diameters to be made, apertures separated by up to 10 m would be required, and suggested a method using a beam-splitter by which this could be carried out, although eventually this method was not used till the modern era of stellar interferometry.

Michelson (1891) tested his ideas by measuring the diameters of the four major satellites of Jupiter, whose diameters had already been determined by other methods, and got excellent agreement. He used a pair of slits with variable spacing to mask the 12-inch aperture of the telescope at Mount Hamilton. He confirmed what Stéphan had already observed, that atmospheric disturbances cause the fringes to shift around, but that they can be followed by an observer's eye and their visibility is not much degraded by the atmosphere. He describes the effect quite graphically in his book *Studies in Optics*, quoted at the beginning of chapter 5. This work was followed up by K. Schwartzschild (1896) and J. A. Anderson (1920) who used the same technique to measure the separation of many binary pairs.

The experiments of Stéphan and Michelson showed one way to achieve diffraction-limited resolution from a telescope. In doing so, they lost the true image-creating capability of the telescope, and this is a loss which is today still proving irksome. Michelson's experiments were intended as a preliminary trial for a much more ambitious project, which would improve on the diffraction limit considerably. This project took another 25 years before bearing fruit.

The instrument which evolved is now known as the Michelson stellar interferometer, a name which distinguishes it from the probably more famous Michelson interferometer used for the Michelson–Morley experiment and the optical determination of the standard meter which earned him the Nobel Prize in 1907. A sketch of the optics of the stellar interferometer and a photograph of it mounted on the 100-inch telescope at the Mount Wilson Observatory in California are shown in figure 1.2. The actual apertures of the interferometers were two 6-inch mirrors mounted on a rigid beam 20-ft long attached to the telescope normal to the line of sight, and whose separation could be changed at will. Using a periscope type of construction, the light from these apertures is brought to within the telescope aperture, and the beams intersect in the image plane, forming an image of the star, diffraction-limited by the 6-inch apertures, crossed by Young's fringes. A great advantage of this arrangement over that used by Stéphan and in Michelson's experiments on Jupiter's satellites, was that the angle of intersection of the beams, and therefore the fringe-spacing, was independent of the separation of the apertures. Although finding white-light fringes in such an enormous system might seem to be an impossible task, since the paths must be equalized to about one micron, in fact the entrance mirrors could be positioned geometrically to better than one millimeter and then a path-compensator next to the observing position was used for final equalization.

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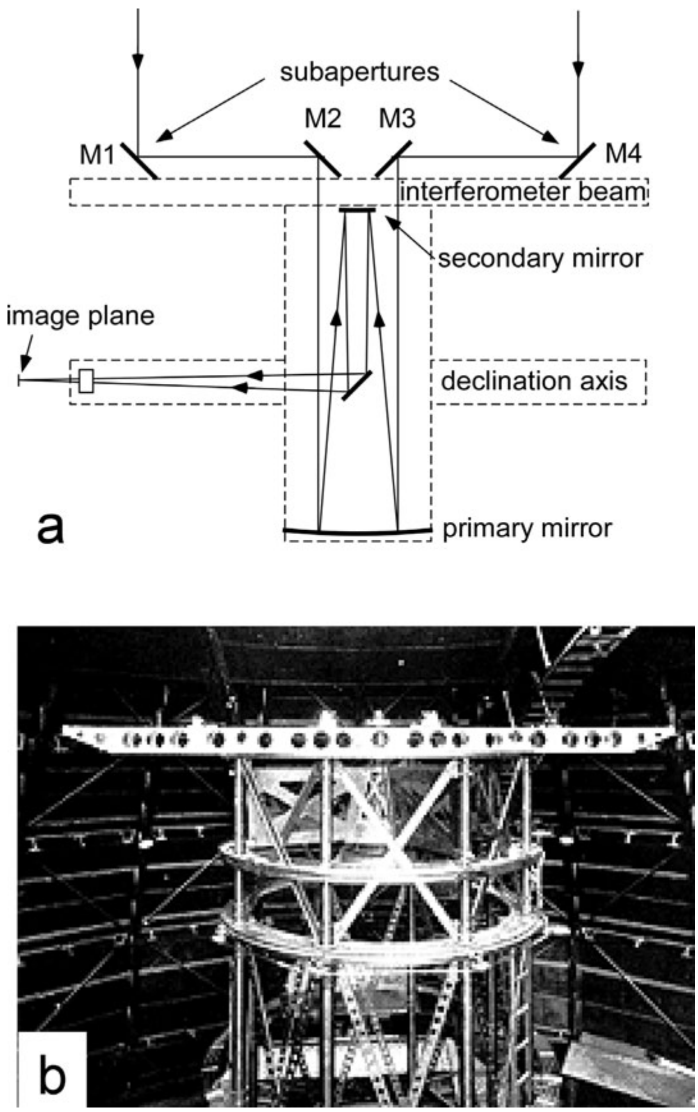

Fig. 1.2. Michelson's 20-foot beam stellar interferometer. (a) Optical diagram; (b) a photograph of the instrument, as it is today in the Mount Wilson Museum (reproduced by permission of the Huntington Library).

This compensator consisted of a glass plate in one beam and, in the other, a pair of glass wedges which could slide laterally on one another to form a parallel-sided plate with variable thickness. A second pair of fairly closely spaced apertures was also observed through the same path-correction optics, allowing comparison fringes with high visibility to be created from the same source and to be observed simultaneously. By partial masking of one of these apertures, fringes with less than unit visibility could be produced, which allowed the observer's eye to be calibrated. Michelson used this instrument to measure the diameter of α-Orionis (Michelson and Pease 1921) and F. G. Pease continued the work with measurements of the diameters of another six stars (Pease 1931). Almost immediately after the success of this instrument, a larger one with maximum separation of 50 feet was designed and built, but by 1931 this had only added measurements of one further star to the list, and work with it was abandoned.

After this period, optical stellar interferometry was essentially neglected for 30 years, since there seemed to be no more stars large enough to be measured this way. But the lessons of the Michelson stellar interferometer were understood in the blossoming field of radio astronomy, and there led to the eventual development of aperture synthesis (chapter 4) by M. Ryle who received the Nobel Prize for this work in 1974. The next breakthrough in optical interferometry came with the work of R. Hanbury Brown and J. Q. Twiss, who invented the intensity interferometer in 1956, a technique which had become possible because of developments in electronics and photodetectors during the Second World War (Hanbury Brown and Twiss 1956). This was implemented using two independent telescopes instead of Michelson's two entrance mirrors and employed separations up to 166 m at the Narrabri Observatory near Sydney, Australia (Hanbury Brown 1974). The theory and results of this method are the subject of chapter 7. But this technique too had its limitations, and was found to be practical with the existing equipment only for stars brighter than magnitude 2.5. When all available interesting stars in the southern hemisphere had been measured, the technique was abandoned around 1974, mainly because of growing successes in a resurgence of optical Michelson stellar interferometry using separated telescopes, which showed greater promise.

One of the strengths of intensity interferometry is that it is oblivious to atmospheric disturbances. This is because the technique works by correlating fluctuations in light intensity at frequencies up to 200 MHz. Since atmospheric fluctuations are limited to frequencies less than 1 kHz, these can easily be filtered out. But, in 1970 A. Labeyrie suggested a revolutionary technique of observation which actually took advantage of the randomness of the atmospheric fluctuations in order to get diffraction-limited images with a conventional large-aperture telescope. This technique, called "speckle interferometry" (Labeyrie 1970), started a revival in interest in high-resolution optical astronomical imaging, described in chapter 6. It was shortly followed by the first successful coherent combination of two telescopes separated by a baseline of 13.8 m (Labeyrie 1975). Once this proof of principle was demonstrated, several groups started construction of large-scale interferometers having several subapertures, and the rest of the story is described in the succeeding chapters.

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1.2 About this book

The plan of this book can be summarized as follows. The following three chapters are devoted to basic principles of optics and interferometry. Chapter 2 introduces the relevant ideas in a very qualitative manner; chapter 3 is devoted to a quantitative discussion of interference, diffraction and coherence, and chapter 4 to aperture synthesis. Chapter 5 discusses atmospheric statistics and turbulence, with a section on adaptive optics which has recently begun to play a role in stellar interferometry. Chapter 6 describes passive techniques used to achieve maximum resolution from single-aperture telescopes, including speckle interferometry and aperture masking. Chapter 7 is devoted to intensity interferometry. Chapter 8 discusses the techniques employed in modern amplitude (Michelson stellar) interferometry with descriptions of the observatories around the world that have been built for this purpose. Chapter 9 describes the "hypertelescope", a way in which many fixed apertures in a very sparse array can in principle be combined to give the equivalent of a very large steerable telescope. Chapter 10 is devoted to three types of instrument devoted to extrasolar planet detection, based on apodization, coronagraphy and interferometric nulling. Chapter 11 aims to present a selection of significant scientific results which have been obtained by them. Finally, chapter 12 discusses future ground- and space-based interferometry systems, also aimed mainly at detecting and imaging planets around distant stars.

Much of the material in the book can be found in recently published reviews. Those we have found particularly relevant and helpful are by Roddier (1988), Lawson (2000), Baldwin and Haniff (2002), Saha (2002) and Monnier (2003). However, the subject is developing continuously, and many of the details in the book will already be outdated before it is published. A useful way of keeping up to date with developments is throught the Optical Long-Baseline Interferometry News (OLBIN) website, http://olbin.jpl.nasa.gov/ edited by P. R. Lawson.

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2

Basic concepts: a qualitative introduction

2.1 A qualitative introduction to the basic concepts and ideas

Interferometric astronomy is founded on the basic principles of interference of light waves, which were first conceived in the seventeenth century by Christiaan Huygens, based on experimental evidence by F. M. Grimaldi and Robert Hooke. Interference itself was studied quantitatively in the nineteenth century, beginning with Thomas Young and Augustin Fresnel, and quickly blossomed into the major subject of physical optics. The first application of interference to astronomy was proposed by Hyppolyte Fizeau in the middle of that century.

The purpose of this chapter is to cover the basic ideas of optical interference relevant to astronomy in a qualitative manner. It is followed by two chapters describing the concepts in a more mathematical way. Some of the tools (particularly Fourier analysis), which are essential to detailed understanding of the subject, but may well be quite familiar to many readers, are described in Appendix A.

2.1.1 Young's experiment (1801–3)

This book is about the application of interference to optical astronomy. The possibility of interference is the major distinction between particles and waves as mechanisms for transporting energy and momentum, and the phenomenon of "destructive interference," in which two disturbances cancel one another out under specific conditions, is peculiar to waves and cannot occur with particles. Although it might seem that energy is somehow being destroyed under these conditions, we always find that the energy which appears to have been lost when two waves interfere destructively appears somewhere else in the system, so that there is, almost miraculously, never any problem with its conservation.

Interference was observed with water waves, for example, long before it was formally described by Thomas Young in England in 1801 (Magie, 1935). Moreover,

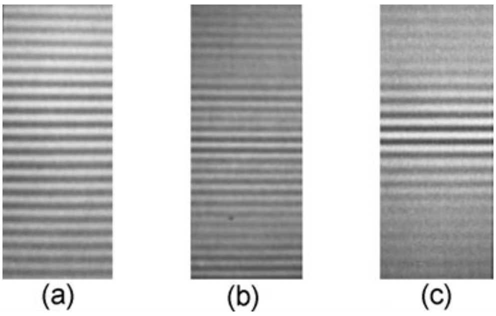

Fig. 2.1. Young's fringes between light passing through two pinholes separated vertically: (a) from a monochromatic source; (b) from a polychromatic line source; (c) from a broad-band source.

the well-known interference phenomenon of beats between sound waves must have been known and used much earlier. But of course there is a world of difference between observing and using a phenomenon and understanding its origins. The idea that light could be described as a wave motion had been proposed over a hundred years earlier by Robert Hooke and by Christiaan Huygens, who had invented the idea of a *wavelength*. However, Huygens had for some reason not alighted on the idea of interference, and his ideas had been more-or-less eclipsed by the weight of Newton's authority which claimed that light was a particle phenomenon.[†] In 1803, Young described an experiment in which a sunbeam, selected by passing sunlight through a small pinhole, fell on a narrow strip of card (1/30 inch wide) and the light beams spreading out from the two edges overlapped on a screen placed after the strip. There he saw a set of bands, "interference fringes," of which the center one was white and the outer ones colored. Cutting out the light from either of the two beams caused the fringes to disappear, so that in the positions of the dark bands the intensity had been *reduced* by adding the second beam while it had been increased in the bright bands. Indeed, Young also remarked on the fact that when one beam was only partially obscured the fringes remained, but with lesser contrast. In a later series of lectures, he idealized this experiment to a pair of pinholes or narrow parallel slits, which is the way in which it is generally presented today (figure 2.1). He used the interference phenomenon, albeit in the form of Newton's rings, to determine for the first time the approximate value of the wavelengths of light of different colors. Young's experiments, carried out more than 100 years after Newton, were analyzed in mathematical detail by a French contemporary, Augustin Fresnel. Because Newton was so revered in England, the further development of the subject

[†] Newton had explained his observation of what are now known as Newton's rings in his *Opticks*, Book II, proposition XII, on the basis of the corpuscular theory, by imbuing his particles with internal vibrations. He thereby came very close to rediscovering Huygens' wave theory. The particles incident on a surface were considered to have "Fits of easy Reflexion" and "Fits of easy Transmission", the interval between them being what we now recognize as half of the wavelength.