Spatial Interferometry in the Mid-Infrared Region

C. H. Townes Department of Physics, University of California, Berkeley, CA 94720, U.S.A.

(Invited article)

Abstract. The potential of high-resolution spatial interferometry for detailed mapping and precision astrometry in the mid-infrared region, somewhat analogous to interferometry now done in the microwave region, is discussed from an instrumental point of view. Some results from a prototype system and from tests of atmospheric properties are given. The design of a more advanced two-telescope system now under construction is outlined. This involves movable telescopes of 1.65 m aperture and of high precision, using heterodyne detection of infrared in the 10 \( \mu \text{m} \) atmospheric window.

Key words: interferometry—astronomical imaging—astrometry—infrared astronomy

1. Introduction

Some years of preparation and experimentation towards a large two-telescope infrared interferometer will come to fruition in 1984–1985. Preliminary work has included construction of a prototype system with a 5.5 m baseline, tests and observations of stars with surrounding dust shells, and astrometric tests. Technical developments include heterodyne detection techniques for the 10 \( \mu \text{m} \) atmospheric window, and engineering of two high-precision, 1.65 m telescopes specifically designed for infrared interferometry. These telescopes will be part of an observational system for both high angular resolution and precision astrometry. They will be mounted on trailers so that the inter-telescope spacing can be varied or the instrument moved from one observing site to another as appropriate. The two telescopes have Pfund-type optics in order to provide high rigidity and stability; the effective stability will also be much enhanced by careful monitoring of all critical telescope parameters with laser interferometers, which will allow correction for any changes. The purpose of the discussion below is to give the background, rationale, pertinent astronomical observations, expected performance, and general design of this interferometer system.

2. Characteristics of the atmosphere in the mid-infrared region

‘Seeing’ is a term to describe atmospheric effects on the quality of a stellar image in a telescope. As generally used, it is a somewhat subjective term, involving judgement of the average size of a stellar image and its motions while observations are being made. This blurring of a stellar image is primarily due to fluctuations in the index of refraction
of the atmosphere, which in turn are due to density variations associated with local
temperature fluctuations, although they can be affected to a lesser extent by variations
in the partial pressure of water vapour. For some time, there have been detailed
theoretical discussions of the effects of local temperature fluctuations available on the
basis of a randomly turbulent atmospheric model. However, only recently have good
quantitative experiments been carried out to examine this type of theory in any detail,
for example to check the wavelength dependence of seeing. At optical wavelengths, the
seeing disk of a star in a large telescope may be anywhere from about \( \frac{1}{2} \) arcsec to 10 or 20
arcsec in size. A disk no larger than 1 to 2 arcsec is generally considered to represent
good seeing. This amount of angular blurring is approximately equal to the diffraction
width due to the telescope aperture, \( 1.22 \frac{\lambda}{D} \), if the aperture has a diameter of 10 cm.
Here \( \lambda \) is the wavelength of visible light and \( D \) is the aperture diameter. The image size in
a telescope of much larger aperture is clearly limited by seeing rather than by the
diffraction beamwidth unless seeing is extraordinarily good. Based on random
turbulence, for fixed turbulent conditions of the atmosphere, the diameter of a
telescope which is diffraction limited increases as \( \lambda^{6/5} \). Thus, at a 10 \( \mu \text{m} \) wavelength
rather than the 0.5 \( \mu \text{m} \) of optical light, the diameter \( D \) of a diffraction-limited telescope
should increase by a factor of approximately 38, to 3.8 m. In this case, the size of the
seeing disk, which is proportional to \( \lambda/D \), decreases as \( \lambda^{-1/6} \). Hence, images produced at
10 \( \mu \text{m} \) should be expected to be approximately 1.8 times smaller in angular size than
those in the visible region under similar atmospheric conditions. The latter conclusion
was first clearly tested by Boyd (1978), who found that, at least under seeing conditions
which gave a rather large stellar image, the ratio of the image size at 10 \( \mu \text{m} \) wavelength
to that at 0.5 \( \mu \text{m} \) agreed very closely with the factor 1.8 predicted theoretically.

There are now a number of observational results using large telescopes near 10 \( \mu \text{m} \)
wavelengths which make it clear that quite large apertures are in fact diffraction limited
at this wavelength. Consider, for example, observations using heterodyne detection of
10 \( \mu \text{m} \) radiation. In this case a CO\(_2\) laser is typically used as a local oscillator, which
mixes with energy received by the telescope in a single diffraction mode, as in the case of
normal heterodyne detection of microwaves in radio astronomy. Intensity of the
received radiation has been examined carefully and found to correspond to essentially
the full power striking the aperture. This shows that all of this power occurs in a single
mode for telescopes as large as 3-m in diameter, the largest so far used with this mode of
Operation (Betz 1981). A still more direct demonstration that telescopes of this size are
diffraction limited at 9 \( \mu \text{m} \) has recently been provided by Bloemhof, Townes &
Vanderwyck (1984). In this case, a linear array of very small infrared detectors was
swept over the image of a star in the 3 m IRTF telescope on Mauna Kea. The resulting
intensity distribution as a function of angle is shown in Fig. 1 for a star with no
surrounding dust, \( \alpha \) Boötes, and in Fig. 2 for two stars which are surrounded by dust
shells. The width and shape of the central peak in all cases agree well with the diffraction
pattern expected at 9 \( \mu \text{m} \). The small bumps at the side of the image of \( \alpha \) Boötes
correspond to the side lobes of the diffraction pattern; those in the images of \( \alpha \) Orionis
and \( \alpha \) Scorpii are primarily due to surrounding dust shells, and represent some of the
fine-scale infrared intensity distribution which needs to be studied with interferometry.

Atmospheric effects in the infrared differ from those in the visible both because the
wavelength is longer and because the index of refraction is different. Table 1 gives the
index of refraction for dry air as a function of wavelength, and of water vapour of the
same density. It can be seen that the index for refraction of air has a very much larger