diction, our conclusion is that the effect of the like-particle excitation, $\delta g_{\mathrm{core}}(\pi h)$, is comparable with that of the unlike-particle excitation, $\delta g_{\mathrm{core}}(\nu i)$. In other words, the $(\sigma\cdot\sigma)\,(\tau\cdot\tau)$ force plays an essential role in the magnetic core polarization. Arita[15] made calculations using various forces and showed that the Rosenfeld force reproduces the experiment when the force range becomes long.

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10-μm Heterodyne Stellar Interferometer*

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A spatial interferometer for 10-μm wavelength which uses two independent telescopes separated by 5.5 m, heterodyne detection of the infrared radiation, and path equalization by a variable-length rf cable, has given interference fringes from radiation of the planet Mercury. Continuous fringe observations during 4000 sec indicate remarkable stability in the optical-path difference through the atmosphere and the two telescopes, fluctuations between 20-sec averages being about $\frac{1}{6}$ of the 10-μm wavelength.

A two-element spatial interferometer, operating with two 10-μm-wavelength heterodyne receivers on a baseline of 5.5 m, has been constructed and successfully tested on an astronomical source. In purpose, the apparatus is similar to Michelson's stellar interferometer in that it provides very high angular resolution of infrared stars and other localized sources; in construction, however, the instrument more closely resembles a long-baseline microwave interferometer.[1,2]

Presently, the interferometer uses the two independent solar auxiliaries of the McMath solar telescope at Kitt Peak National Observatory.[3] Each auxiliary telescope consists of a flat heliostat of about 0.4-m^2 collecting area followed by a fixed off-axis focusing mirror and subsequent optical flats which direct the beam to a fixed focus at a receiver. The total optical path within each telescope is about 120 m. The steerable flats of these two separate telescopes are situated on an east-west baseline with a center-to-center separation of 5.5 m. An interferometer of this type can resolve angles as small as about $\lambda/2D$, where λ represents the wavelength of the received radiation, and D the separation between the receiving apertures. There are many astronomical sources of intense 10-μm radiation which have not been resolved and which are thought to have angular dimensions between 1 and 0.01 arc sec, requiring baselines between 1 and 100 m to be resolved. Some of these objects have essentially no visible radiation; others are visible stars with circumstellar dust clouds of unknown size and shape which emit the dominant part of the 10-μm radiation.

At each focus of the two separate telescopes, a high-speed Ge:Cu photoconductor mixes the stellar radiation with a local oscillator beam from a stable 1-W CO_2 laser[4] as indicated in Fig. 1. The radio-frequency signals from each photomixer preserve the original phase and amplitude characteristics of the infrared radiation. The photomixer outputs are each amplified and passed through a stepped coaxial-cable delay line which compensates for the changes in optical path length produced as the infrared source is tracked across the sky. For interference of two beams over a frequency bandwidth $\Delta\nu$, the path lengths must be equalized to within a distance small compared with $c/\Delta\nu$ to avoid any significant correlation loss. Hence, the 1200-MHz bandwidth of these signals requires that the delay cable be maintained accurate to a few centimeters. In a direct-detection interferometer, such as Michelson's original instrument, the relatively large signal bandwidth enhances sensitivity but requires accuracy of optical path lengths comparable with the wavelength of the light involved, which is considerably more demanding than the delay-cable accuracy required for an inherently narrow-band heterodyne interferometer.

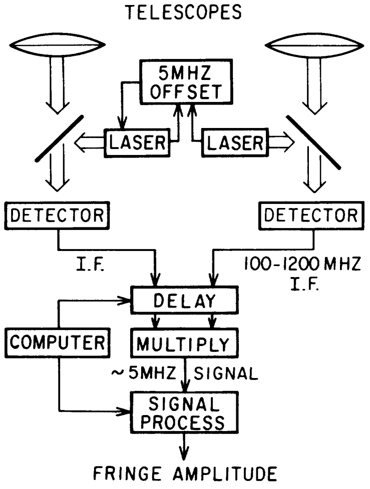

FIG. 1. Schematic diagram of infrared heterodyne interferometer. Separation of telescopes is 5.5 m.

Following the rf delay line is a broad-band correlator which multiplies together the two appropriately delayed photomixer signals. The correlator output signal represents the fringe amplitude; it is proportional to the degree of coherence between wave fronts arriving from the source at the two receivers and, for a given flux, approaches zero for a source which is resolved. The frequency of this signal depends on the motion of the source through the interferometer fringe lobes and on the frequency difference between the two laser local oscillators. In order to produce a fringe signal convenient for processing and to avoid undesirable interaction between the lasers, the local oscillators are phase-locked with a 5-MHz frequency difference. This 5 MHz frequency is later removed from the correlator output signal in a single sideband demodulator, yielding the natural fringe signal. For a horizontal east-west baseline the natural fringe frequency is given by $\Omega D(\cos\delta)(\cos H)/\lambda$, where Ω is Earth's rotation rate, δ is the source declination, and H is the source hour angle, which increases linearly with time.

The planet Mercury was the strongest convenient source on which to test the interferometer. Its diameter at the time of measurement was 6 arc sec, or about 10 times the fringe lobe spacing, and hence its disk was resolved. However, Mercury was at maximum elongation from the sun, so that its temperature distribution was strongly peaked toward the subsolar edge of the planet. The resultant fringe modulation signal was comparable with the level expected from the strongest 10-μm "infrared star," IRC+10216, and 5 to 10 times greater than that expected from the red giant star Betelgeuse. Mercury was observed in late July and early August 1974, after

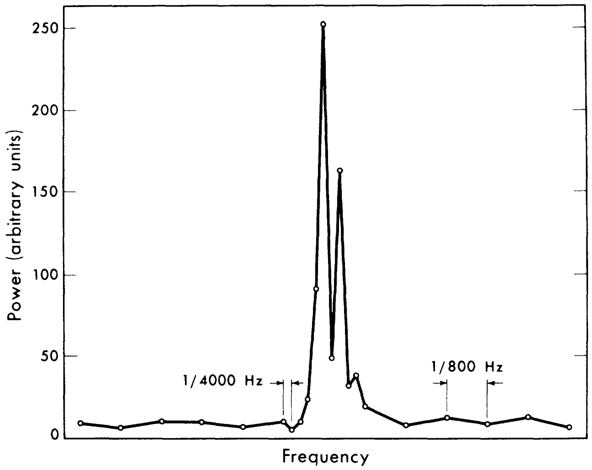

FIG. 2. Power spectrum of correlation signal. The root-mean-square system noise in units of $\frac{1}{4000}$ Hz is approximately 3 units. Most of the fluctuations in the above data are attributed to signal variation due to atmospheric instability.

sunrise between 15° and 45° above the eastern horizon, yielding natural fringe frequencies between 4 and 20 Hz.

Information about fluctuations in the relative phase of infrared signals arriving at the two telescopes was of primary interest in these initial tests. Such fluctuations, caused largely by the atmosphere, are expected to be the limiting factor for stellar interferometers operating at visible and infrared wavelengths. The correlation signal from Mercury was expected to be centered in frequency at the theoretical value predicted from the parameters of the planet's motion and of the interferometer baseline, but broadened in frequency by atmospheric phase fluctuations. Therefore, a power spectrum centered at the predicted frequency was computed from recorded data taken during 4000 sec of continuous observation. Figure 2 shows a composite spectrum with a resolution of $\frac{1}{4000}$ Hz at the center—the smallest frequency interval justified by the length of observation. In the wings of the line, a resolution of $\frac{1}{800}$ Hz is used. It is seen from this figure that a substantial fraction of the signal energy falls within an exceedingly narrow spectral width, and that some signal is spread over a much wider spectral region. The central peak, while very narrow, was displaced about $\frac{1}{40}$ Hz from the calculated value, presumably because of some imprecision in the determination of the required parameters. In the wings of this signal, the power spectrum is approximately proportional to $(\nu - \nu_0)^{-2/3}$, where $\nu - \nu_0$ is the deviation from the central peak, and is noticeably above noise as far as about $\frac{1}{10}$ Hz from the central peak.

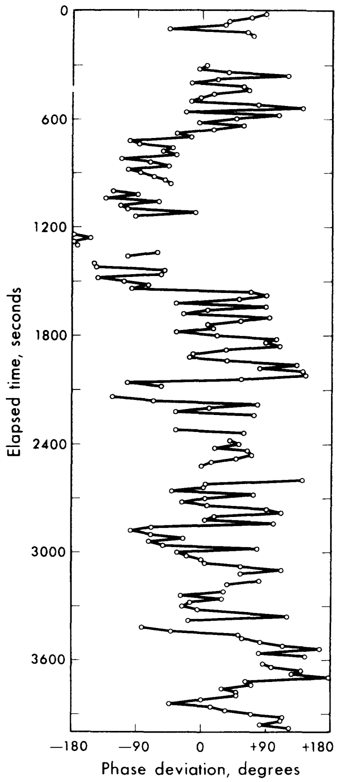

FIG. 3. Phase deviation from predicted frequency. A linear slope corresponding to $\frac{1}{40}$ Hz has been removed. Points for which power at the predicted frequency dropped below 15% of the mean are not plotted. In the absence of atmospheric fluctuations, system noise would be expected to produce approximately a 30-deg root-mean-square deviation.

The unexpectedly long-term coherence of the signal made evident by Fig. 2 suggested a direct computation of the phase difference between the correlation signal and the predicted interference-fringe frequency. Figure 3 shows successive 20-sec averages of this difference, which exhibits little tendency to wander from a constant and has a root-mean-square deviation of only 60 deg. Previous tests with the same fringe-detecting apparatus of the propagation fluctuations within the solar-telescope building showed them to be comparable with those seen in the signal from Mercury. Hence even the small phase variations observed may be associated largely with fluctuations of the two separate 120-m optical paths within the telescope structure, or with imperfect tracking of the telescopes on Mercury, rather than with essential atmospheric effects. These phase fluctuations within the telescope system can be compensated in later versions of the instrument by reference laser beams.

The high degree of coherence indicated by Fig. 2 was obtained on one morning out of about six periods of observations when the "seeing" was relatively good (angular fluctuations $\simeq 1$ arc sec). Other observations frequently showed the fluctuations to be much larger in both amplitude and rate of change, but these have not yet been analyzed in detail. The greater part of the observation was made with Mercury low on the horizon, for which the projected separation between telescopes was about 2 m, and the planet was viewed through approximately 3 times greater depth of atmosphere than would occur at the zenith.

While the signal-to-noise ratio was quite adequate for this initial test, further improvement is important for the wide variety of astronomical measurements which can be envisaged. Atmospheric seeing is sufficiently good that larger telescope apertures may be used to increase the signal strength by about 1 order of magnitude. The system noise for heterodyne detection has a theoretical minimum value proportional to $h\nu$ per unit bandwidth for a photon frequency ν.[5] The Cu-doped germanium detectors used had a noise level about 25 times larger than this limit, but other detectors (HgCdTe photodiodes in particular) have been demonstrated with noise as small as $4h\nu$, and hence improvement by a factor of 6 appears practical. The integration time can of course be longer than the 68 min used here; less well known is how stable the relative phase differences through the atmosphere may be under the best of seeing conditions or with greater distances between telescopes. Less stability would decrease the effective signal-to-noise ratio obtainable for a given system. Under good seeing conditions infrared stellar images can be smaller than what appeared to be the case during this observation. It is thus reasonable to expect coherence times even longer than the 4000 sec obtained in this experiment, and a still larger fraction of the signal energy within a very narrow spectral width. However, any firm evaluation of fluctuations under other conditions must await further measurement.

Atmospheric stability, while still incompletely known, seems adequate to allow extensive interferometry on astronomical objects at infrared wavelengths comparable with or longer than 10 μm, and a wide variety of infrared spatial interferometers may be envisaged. Longer baselines of variable length and orientation are needed; it is for such use that heterodyne detection and path-length equalization by rf cables are especially convenient. The present two-element system can measure sizes of some of the brighter localized infrared sources, and improvements noted above should allow examination of the brightness distributions of a large number of infrared astronomical objects under very high angular resolution. In addition, the rms phase fluctuation of 60° found for each of about 200 determinations during the present observation suggests that the position of Mercury was determinable from this experiment with a precision of about 0.01 arc sec. This gives some promise that measurements of fringe phase will allow highly accurate determinations of stellar positions or of Earth's rotation.

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