THE ASTRONOMICAL POTENTIAL OF SPATIAL INTERFEROMETRY IN THE INFRARED

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ABSTRACT

The angular diameters and shapes of bright infrared stars are now being measured from 2 micron to 20 microns using several newly developed techniques of high angular resolution interferometry These objects possess circumstellar shells emitting in the temperature range 300-600K, thus the brightest of their number have sizes ranging from 0 1 to 10 arcseconds, and are readily resolved by instruments a few meters across.

The size, shape, and structure of several types of stars will be discussed in detail as the Colloquium proceeds It will be seen that this information can be used to help characterize the optical properties of the particulate material contained in the circumstellar envelopes. Conclusions concerning the formation and evolution of these cold outer regions of stars may also be possible. It appears that the conditions in some of these circumstellar envelopes may be suitable for the formation of planets, a process which may be studied directly as these new techniques are further developed.

Although sensitivities of present instruments are still somewhat marginal, it is now possible to resolve the brightest of the extragalactic nuclei at 10 microns Future instrumental developments should bring the size and structure of many extragalactic nuclei within reach at several wavelengths, thus adding important information on the nature of these extraordinary sources of infrared emission

1. INTRODUCTION

The pursuit of high angular resolution in the infrared has led to the development of interferometers using both coherent (heterodyne) and incoherent (bolometer and photovoltaic) detectors. These two approaches are to be discussed in detail later in the program by their respective proponents at University of California, Berkeley and at University of Arizona. Here an attempt is made to show how interferometric measurements, carried out at angular resolutions of 1.0 - 0.01 arcseconds and at flux levels of 10 - 10^4 Jy, can contribute significantly to our knowledge and understanding of infrared sources. Data presented later in the colloquium will show that, in several wavelength bands accessible with ground based telescopes, angular resolutions of 0.1" and sensitivity of 40 Jy have already been achieved. Further improvements can be expected which will extend both sensitivity and angular resolution in all the atmospheric windows from 2 to 1000μm. It is beyond the scope of this paper to speculate on the almost unbounded possibilities that lie ahead if these techniques are applied in space experiments where both wavelength and background limitations are virtually removed.

The following brief illustrations show several specific areas of study where infrared spatial interferometry may be applied to provide important information on angular size, shape and structure. It will be seen that high potential exists in areas of research extending from the solar system to the study of extragalactic sources, with perhaps the greatest potential in the study of circumstellar envelopes as they relate to the formation of stars and planets.

2. SOLAR SYSTEM

Spatial resolution has always been a limiting factor in the study of planetary bodies and this is especially true in the infrared where the planets emit their thermal radiation. The highest spatial resolution has been obtained by spacecraft instruments carried close to a planet. In principle ground based telescopes operated as interferometers can achieve both the necessary sensitivity and resolution to answer many of the questions which must otherwise wait for space experiments of much greater cost.

Mr. Howell, of our group at University of Arizona, will describe later in the program an example of ground based infrared spatial interferometry involving the question of polar ice caps on the Galilean satellites. Jupiter itself offers other possibilities.

At a wavelength of 5μm the planet Jupiter appears as a cold disk, ∿140K, accented by small "hot spots" corresponding, we think, to structures in the cloud layers where hot underlying layers of the atmosphere (∿300K) can emit directly to space. This phenomenon has been studied extensively at the University of Arizona[1] and at the California Institute of Technology,[2] where even with the 5-m telescope the smallest structures remain unresolved. A much more detailed study of individual hot spots, as they form and evolve over a period of days, could now be carried out from the ground with an interferometer at 5μm.

3 STARS WITH CIRCUMSTELLAR ENVELOPES

The nature of circumstellar envelopes--their size, shape, radial structure, composition, temperature, energetics, variability, and expansion or contraction, along with their role in the life of highly evolved stars, their interaction with the interstellar medium, and the development of very young stellar and planetary systems--is a major part of infrared astronomy.

Even though lunar occultations have provided important information on the sizes of certain objects,[3,4] it was not until the advent of infrared interferometry that more detailed measurements of sizes, shapes, and radial structures became possible.[5-10] Table 1 summarizes the status of our work at the University of Arizona. It shows the various wavelengths at which observations are made and gives approximate diameters for 15 stars of several types which have circumstellar envelopes that have been resolved. For a few of the brighter objects both size and shape information has been obtained, and Dr. D. McCarthy will discuss these observations and some of their consequences. Several of these stars have been studied at 11μm by the Berkeley group using their coherent interferometer with larger baselines up to 5.5 meters, and these results will also appear later in the

Table 1. "Resolved" Stars

Class	Object	θ_m	Angular Diameter (arcsec) vs. Wavelength (μm)								Comments
			2.2	3.5	5.0	8.4	10.2	11.1	12.5	20	
M Ia	α Ori	0.64	≤ 0.050		≤ 0.050	≤ 0.050	>2.0	>1.0	>1.0		
	α Sco	0.44	≤ 0.050		≤ 0.050	≤ 0.050	~ 0.25	~ 0.20			
	μ Cep	0.24				<0.1	~ 0.25		~ 0.25		
Proto Star	VY CMa	0.39			0.2	0.35	0.7	0.6			flattened
C	IRC+10216	0.64			[ranges	from	0.25 to	2.0	]	<6.3	flattened
	IRC+20370	0.074			~ 0.15						
	V Cyg	0.097		<0.05	<0.05		~ 0.2				
	CIT 6	0.051			~ 0.15		~ 0.2		~ 0.3		variable?
Miras	o Ceti	0.044			≤ 0.10		~ 1.0				phase-dependent visibilities?
	R Leo	0.031			≤ 0.10	≤ 0.10	$\gtrsim 0.25$				
	χ Cyg	0.021			≤ 0.10		$\gtrsim 0.3$				
Others	IRC+10420	0.52			~ 0.3	~ 0.4	~ 0.4		~ 0.5		F8-GOI
	HD 44179	2.2			~ 0.25						"Red Rectangle"
	GL 2688	2.6					>1.0				"Egg Nebula"
	NML Cyg	0.27		0.12	0.18	0.4	0.4	0.4	0.4		flattened
	JIV	0.97						~ 1.21			

$$\theta_m = \frac{8.2F_\lambda}{B_\lambda(T)} \times 10^5 \text{ arcsec} \; ; \; \lambda \equiv 10\mu\text{m}$$

program. Our observations are made at aperture spacings of 0.9, 1.2, 1.9, and 3.2 meters, using telescopes of the University of Arizona and the 4-m telescope at Kitt Peak National Observatory. Soon we hope to extend our baseline to 7 meters when the new Multiple Mirror Telescope (MMT) located on Mount Hopkins becomes available

Our interferometric studies of circumstellar envelopes are concerned with the measurement of visibility--i.e., ratio of fringe signal to photometric signal--as a function of baseline and position angle at a sufficient range and number of wavelengths to separate the hot inner layers from the cold outer layers of emitting material Only in this way is it possible to arrive at a correct and quantitative picture of the distribution of dust around the star. Equipped with this data and the spectral energy distribution it should be possible to construct models which delineate many of the physical properties of such systems

Although it seems likely that planets are forming within certain of these circumstellar disks, our resolving power and sensitivity are not yet sufficient to detect this process directly. However, it is now possible to add substantially to the knowledge of the physical conditions which exist within these disks of gas and dust which may evolve into planetary systems

In other highly evolved stars where large amounts of material are being ejected to sustain large, dense envelopes of gas and dust, the opportunity exists by selecting the proper wavelength bands to study various components of the material which ultimately collects in the space between the stars to form the interstellar dust clouds

4. THE K-L NEBULA, A COMPACT CLUSTER OF NEW STARS

The prime example of a nearby compact cluster of proto-stellar objects is shown in Figure 1. These maps at 20μm show the nebula at resolutions of 15 arcsec[11] and 5 arcsec [12] Figure 2 compares the high resolution map at 20μm to maps at other wavelengths and clearly shows that there is a cluster of cold discrete sources within the nebula. Higher resolutions should not only resolve individual stars but should further resolve the cluster into its separate parts. Recently spectroscopic evidence has

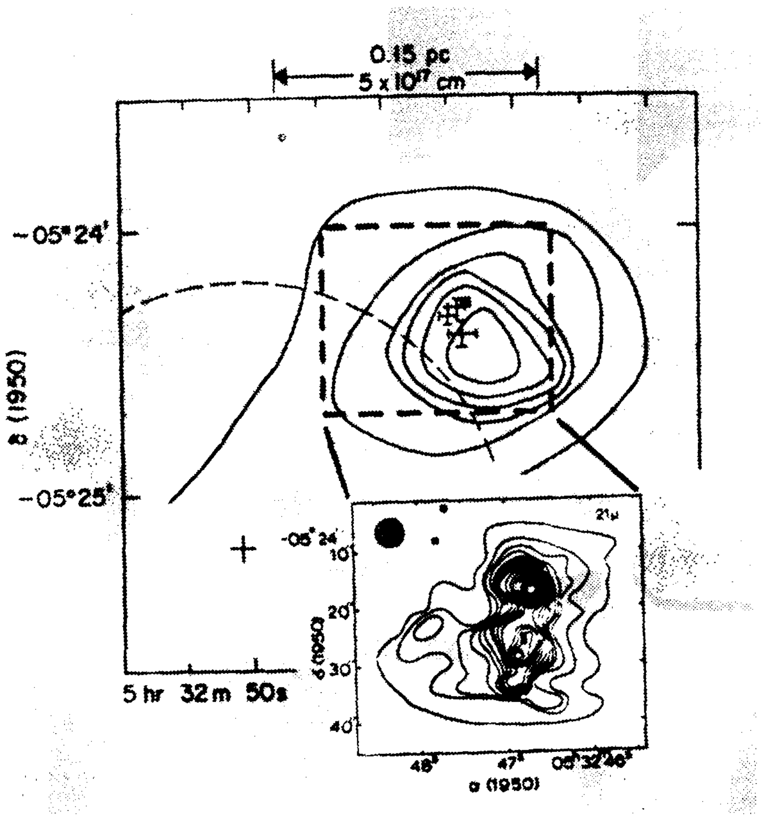

Figure 1 The Kleinmann-Low Nebula at 21μm is resolved into a compact cluster of protostars at 5 arcsecond resolution.

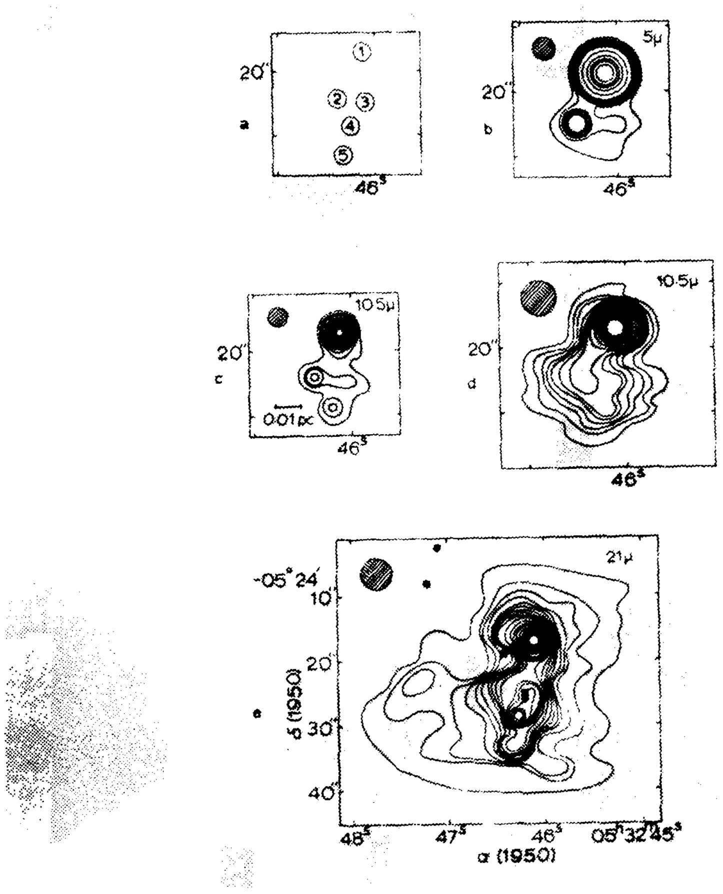

Figure 2. The same 21μm high resolution map compared to similar maps at shorter wavelengths

indicated[13] that B-N, the hottest and brightest member of the cluster, is extremely young. It is likely that the colder members are even younger in the evolutionary sense and that at very high resolution and sensitivity even more primitive objects may be found.

5. THE GALACTIC NUCLEUS

Figures 3, 4 and 5 show the core of our galaxy at 10μ as it appears, hidden from ordinary view by interstellar dust, at resolutions of 20, 6 and 1.5 arcseconds The role of high angular resolution in continuing the study of this extraordinary region is dramatically illustrated by these maps[14] taken from a recent paper by Rieke, Telesco and Harper In their paper these authors give a detailed discussion of these sources and continue the hot debate over the nature of these cool objects

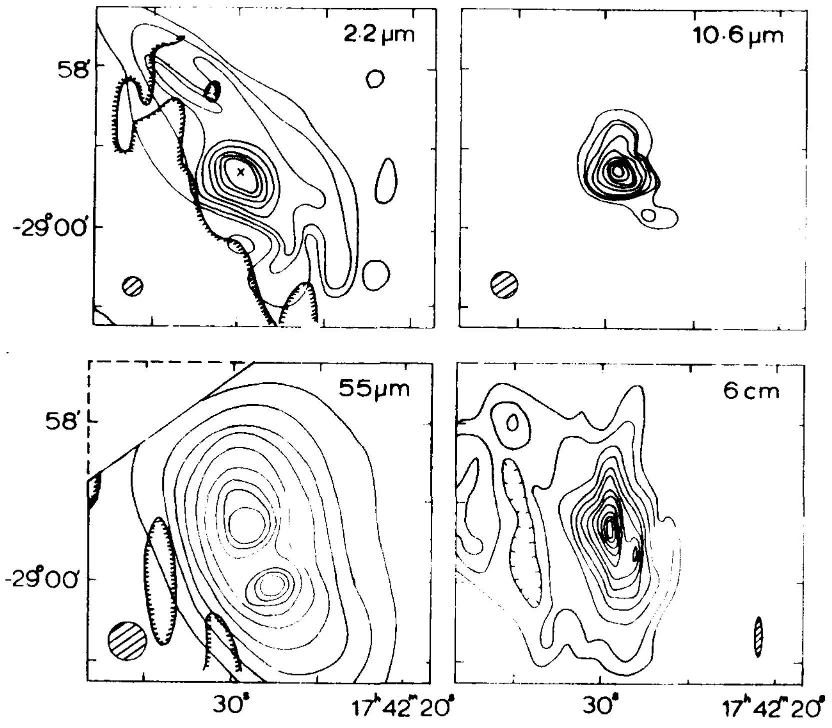

Figure 3 The galactic nucleus (Sgr A) at 10.6μm and 20 arcsecond resolution.

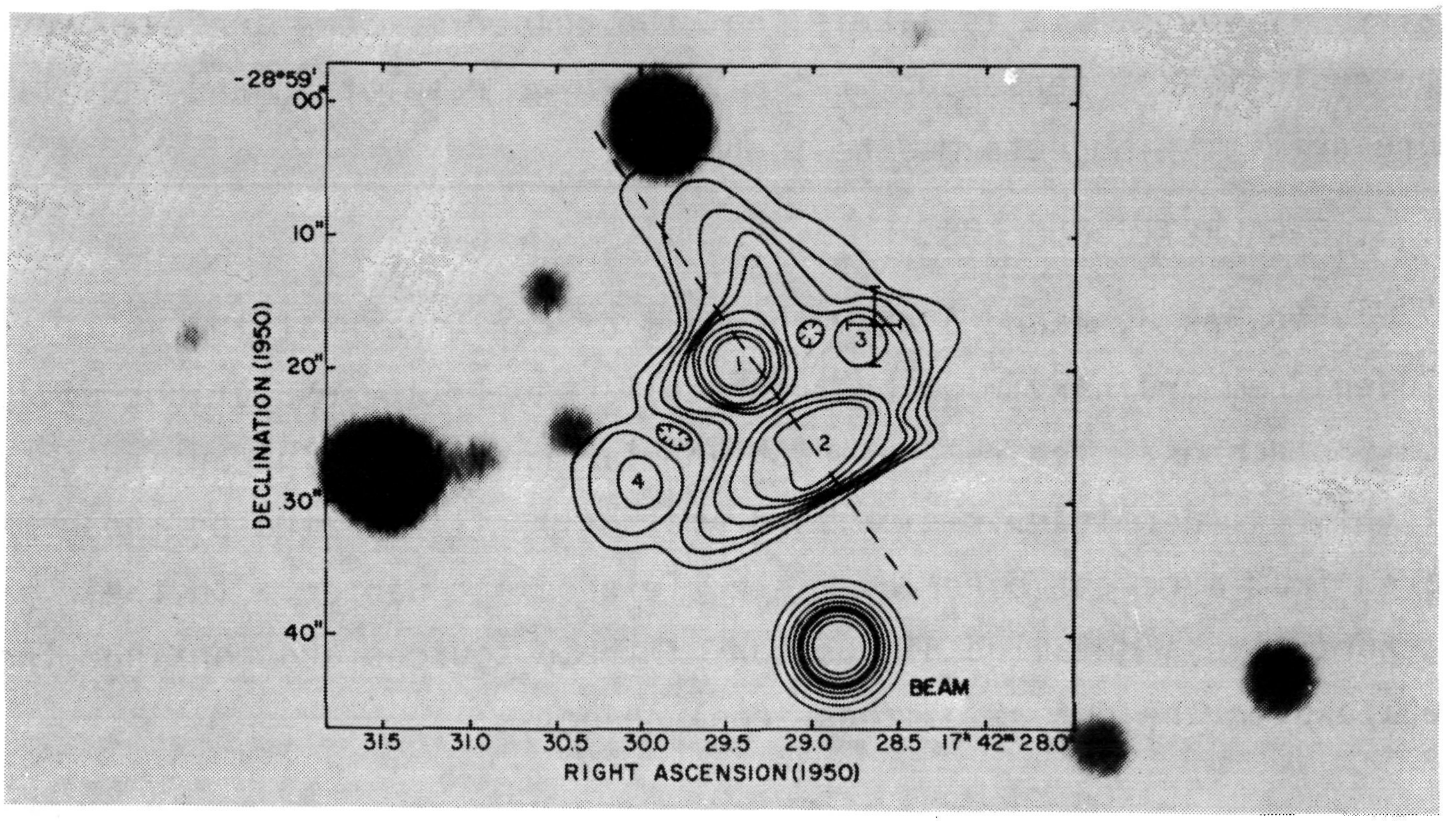

Figure 4. The galactic nucleus at higher resolution (6 arcseconds).

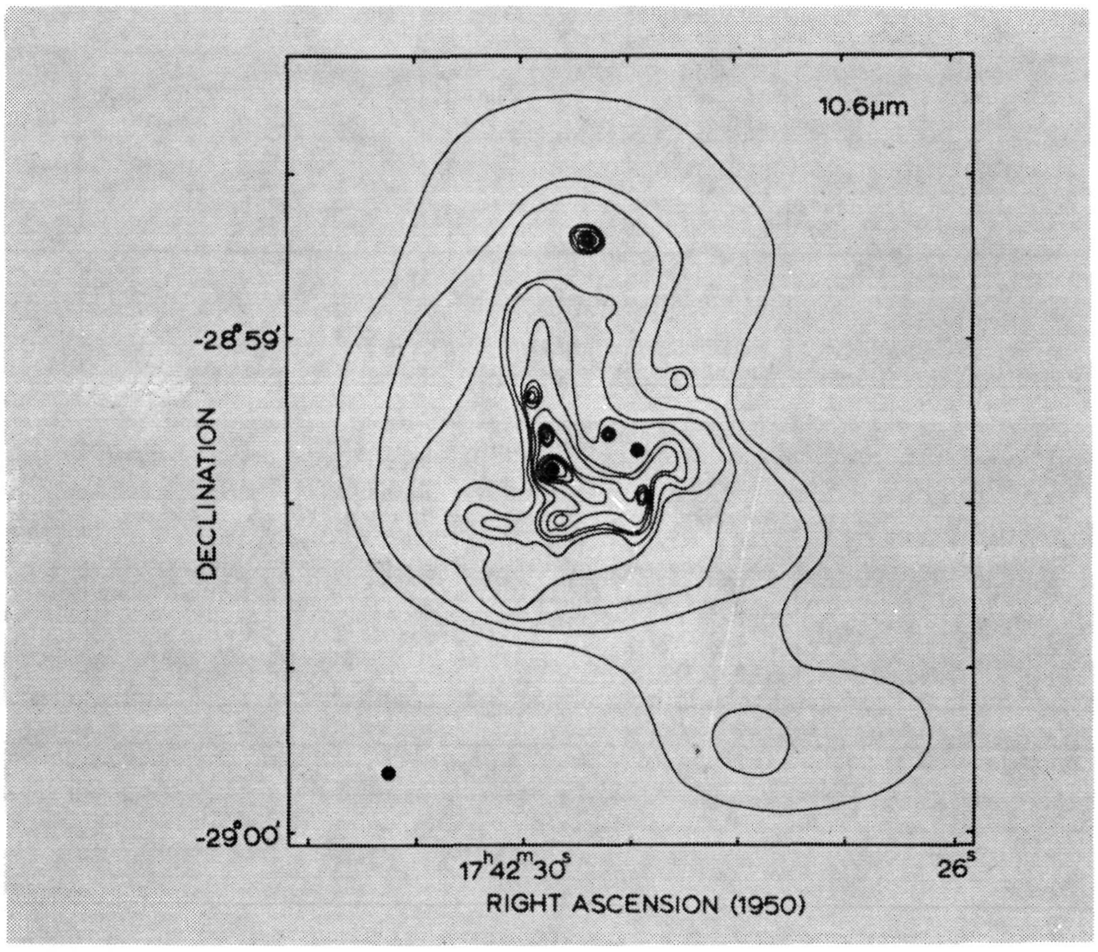

Figure 5 The galactic nucleus at a resolution of 1.5 arcseconds, clearly showing many resolved components.

6. EXTRAGALACTIC SOURCES

Information on the size and structure of extragalactic sources in the infrared can be gained at a moderate resolution since in a number of galaxies, such as M82, the nucleus is larger than 10 arcseconds.[15] However, just as in the case of our own galaxy, higher resolution shows more detailed structure, Figure 6. Note that the 2 - 3 arcsecond resolution of this 10μm map,[16] obtained by Rieke and Low using the 2.3 m telescope of Steward Observatory at full aperture, shows a complex structure similar to, but not identical with, the radio map of comparable resolution. Higher resolution should reveal further details and possibly resolve the brightest sources in the nucleus of M82.

Within our present range of sensitivity there is at least one other galaxy of great interest, the bright Seyfert, NGC 1068. In order to study the structure of its nucleus at 10μm, a resolution of 0.1 arcsec or better is needed. Using the 5 m telescope at Palomar, Neugebauer and Becklin[17] have resolved the nucleus at 10μm, but its structure below 1 arcsec remains

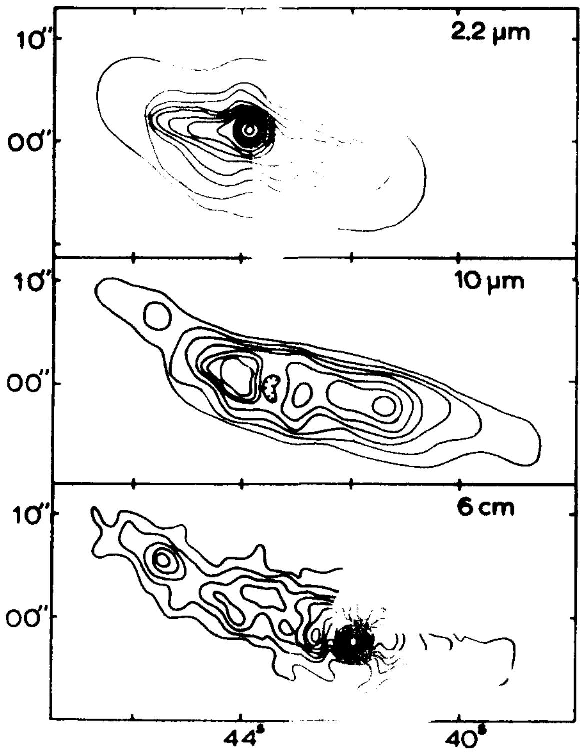

Figure 6. Unpublished maps of M82 at 2.2μm and 10μm compared with a radio map of comparable resolution (2-3 arcseconds).

to be determined The outer parts of the nuclear source are probably optically thin dust heated by an enormously luminous core. This inner core may also emit in the infrared as in the case of variable sources such as BL Lac which are thought to be nonthermal It is also quite possible that the nucleus of NGC 1068 may consist of a number of powerful discrete sources, each of similar character

7 CONCLUSIONS

Exciting areas for astronomical research lie ahead, even with the relatively short baselines now available for infrared instruments Obviously sensitivity and accuracy must be pushed as close as possible to their fundamental limits Also an even wider range of wavelengths is necessary since much information is lost when either the hottest or coldest parts of these complex sources are left unresolved.

Plans for larger baselines should take into account the following requirements:

(1) Minimum instrumental background to maximize S/N.

(2) The ability to vary baseline and position angle independently.

(3). An efficient means of measuring the fringe signal and the photometric signal simultaneously to improve the accuracy

8. ACKNOWLEDGEMENTS

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DISCUSSION

L. Mertz: Aren't there difficulties in producing maps of non-centrosymmetric objects?

F. Low: Yes. That is why we need to measure the fringe visibility for as many baseline lengths and position angles as possible.

C.H. Townes: The way to map an asymmetric distribution is to measure the fringe phase. While this is not easy, it can be done by some types of infrared interferometer.

I would like to add three more topics to Professor Low's interesting list of areas of study.

(1) Astrometry. The technical aspects of infrared astrometry will be

discussed by Dr. Storey tomorrow (Paper No.20). The main point to note is that there are some types of object which can only be studied in the infrared, since they emit strongly only in this spectral region,

(2) The measurement of stellar disk diameters. Professor Low has concentrated his discussion on dust shells, which are larger than the stellar disks themselves Baselines about one order of magnitude larger are needed to resolve the disks, and such resolution would be particularly useful for those stars which are so surrounded by obscuring dust shells that they can be studied only by infrared interferometry.

(3) Spatial resolution in infrared emission lines. This topic may be a little less obvious to astronomers than the other two. For example, Geballe, Lacy and Beck have recently found in VY CMa P-Cygni-type line shapes for SiO lines in the 10 μm region. A narrow band spatial interferometer could separately examine the distribution of absorption and emission in these lines, and also of dust emission.

A second example is the infrared fine structure lines found in HII regions. While many HII regions in our Galaxy are large enough to observe conventionally, Geballe et al. have shown that G333.6-0.2 has remarkably intense emission in the Ne II 12.8 μm line, originating in a region at least as small as 2", and better resolution by an interferometer seems needed.

In addition, Lacy et al. have found a number of ionized clouds, of size about ¼ pc, each moving at its own velocity in our Galactic center and emitting reasonably intense Ne II 12.8 μm radiation. If similar clouds exist in the nuclei of other galaxies they might be resolved and studied by infrared interferometry. While such studies would require some special efforts, both the Ne II and circumstellar molecular lines are intense enough to be so studied by presently known interferometric techniques.