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Infrared Astrophysics

New observational techniques reveal physical properties of infrared stars, nebulas, and galaxies.

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It is not difficult to see why the astronomer has largely neglected the infrared region, even though it was discovered by William Herschel at the beginning of the 19th century. Until recently, the infrared astronomer dealt mainly with the planets, realizing that ordinary stars and galaxies become quite faint in the infrared. Radio astronomers have consistently pressed to higher and higher frequencies only to find that, in general, the bright radio sources also become increasingly faint as the infrared wavelengths are approached. Today, however, we have a substantial list of bright infrared sources which radiate principally, if not exclusively, in the wavelength interval from 1 to 1000 microns. The fact that these infrared stars, nebulas, and galaxies exist constitutes the principal reason for a much more vigorous effort at these wavelengths than could be foreseen a few years ago.

Many of the current observations are made with a device which is merely a refinement of Herschel's original thermal detector. The main difference between the thermal detectors of the last century and those now in use is the extremely low temperatures which are now employed. These and other recent advances in infrared observational capabilities will be discussed here, and it will be shown how they are leading to unexpected results of great astrophysical importance.

Infrared Detectors

Both radio and optical detectors are more sensitive than modern infrared detectors. This discrepancy in performance is not fundamental and should ultimately disappear as the technical inconveniences which cause the problem are overcome. Until the ultimate infrared detector is developed, we must select from a large number of devices which fall into only two basic categories: (i) the photodetector, which relies on the solid-state equivalent of the familiar photoelectric effect; or (ii) the thermal detector, which operates on the principle of the simple conversion of radiation to heat and the detection of the resulting rise in temperature.

The latter technique dates back to Herschel and is typified today by the germanium bolometer (*1*) operated at 2°K. The large number of photodetectors that have been developed attests both to the great emphasis they have received and to the fact that each photodetector is, by its nature, restricted to a relatively narrow range of wavelengths. The difference in spectral response is, in fact, the chief distinguishing feature of the two types of detectors; that is, the thermal detectors have inherently a flat energy response, whereas the photodetectors tend toward a flat photon response out to a maximum wavelength where the response drops rapidly to zero. Another fundamental distinction is that photodetectors are confined to the domain of semiconductor physics. Although semiconductors are sometimes used in thermal detectors, many other types of temperature-sensitive phenomena are equally useful.

For simplicity let us consider only "cooled" thermal detectors and "cooled" photodetectors, noting that the degree of cooling need not be the same in each case. In general, the amount of cooling required in a specific application is determined by how thoroughly the detector must be decoupled from the ambient thermal fluctuations in order to ensure that the main source of noise is the inherent fluctuation in the incident stream of photons. These photons originate either in the source itself or in the background on which the signal is superimposed. For example, room temperature fluctuations limit an uncooled thermal detector to a sensitivity of about 10^{-10} watt hertz$^{-1/2}$; uncooled photodetectors are limited to wavelengths of less than about 7 microns.

The physics of the low-temperature germanium bolometer is extremely simple and illustrates very well one approach to the detector problem. A single crystal of germanium is doped with impurities which cause the electrical resistance to be of the right order of magnitude and to change rapidly with temperature from 1° to 4°K. This temperature range is chosen because it is easily maintained with the use of liquid helium as the coolant. The resistive element is mounted in a vacuum and loosely coupled to the helium-cooled heat sink so that a small amount of radiation absorbed in the element causes a large rise in temperature. For example, at 2°K thermal agitation is low enough so that a temperature rise of only 10^{-7} °K is measurable, leading to detection of inci-

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dent power levels as low as 10^{-14} watt in 1 second of integration. It is a straightforward problem to blacken the element so that it absorbs almost totally at any wavelength. Fortunately, the heat capacity, which varies at low temperatures as T^3, is quite small, permitting rapid response to modulation of the signal.

It can easily be shown that the fundamental limit of sensitivity of such a detector is set by purely random thermal fluctuations which decrease in strength as the absolute zero is approached. The measured performance of the detector just described approximates this theoretical limit; the expected $T^{5/2}$ dependence has been demonstrated from 4°K down to 1.5°K. In principle, at least, the performance of a thermal detector can be improved indefinitely by cooling to lower and lower temperatures. If the coolant were the isotope He^3 instead of ordinary helium, the operating temperature could be reduced by a factor of 10; and, theoretically, power levels of 10^{-17} watt might be detected. This corresponds to a flux of 100 quanta per second at a wavelength of 3 microns.

In order to use such enormous sensitivity, the incident background must be reduced to levels far below those encountered in most present-day applications. Before this can be accomplished there are complications independent of the detector which must be dealt with.

Infrared Telescopes

In order to be useful for astrophysical purposes, the infrared detector is coupled to a telescope. If the telescope is ground-based, atmospheric constituents, particularly CO_2 and H_2O, restrict its use to certain wavelength intervals, or windows, in which these absorbers are at least partially transparent. Thus, between 1 and 25 microns there are several good windows centered, at 1.6, 2.2, 3.4, 5, 10, and 22 microns; but from 25 to 1000 microns there is almost total extinction, even from the driest sites. In addition to absorbing many wavelengths, the atmosphere radiates into the telescope a large, slowly varying, background signal. Fortunately, most of the fluctuating component of the sky brightness can be canceled, but the remaining "sky noise" is still well above fundamental photon noise and severely limits the performance of ground-based telescopes. Since the problem of discriminating faint sources against a noisy background is fundamental in infrared work, these considerations dominate all others in the design of the telescope.

Infrared observations have been carried out at all available wavelengths on a variety of large optical telescopes of conventional design. Cancellation of sky noise is better on small telescopes so that, at 10 microns, the limiting magnitude with a 28-inch (71-cm) telescope is comparable to that with the 200-inch (510-cm) Hale telescope. Furthermore, any significant degradation in the image quality of a large infrared telescope increases the background on the detector and degrades its ability to reject sky noise. Experience has shown that from 5 to 25 microns the image should approach the diffraction limit, and that the idea of building very large telescopes of low resolution for the longer wavelengths is basically unsound.

Thus far, the most effective technique for modulating the signal from a star while rejecting the background has been to use the secondary mirror of a Cassegrainian telescope to translate the star image rapidly through a small arc just larger than the detector. Since this is only feasible with rather small telescopes, there is again a practical limit imposed on the size of ground-based telescopes. At present, the optimum size would appear to be between 30 and 60 inches for wavelengths between 5 and 25 microns. Much larger telescopes can be used profitably for shorter wavelengths and for 1000 microns since the sky brightness is much fainter.

Another approach is to carry the telescope above the troublesome layers of the earth's atmosphere. High-performance jet aircraft and large balloons are capable of lifting instruments above most of the absorbing and radiating layers. Even at an altitude of 12,000 meters, the improvement in transparency and in sky brightness over the best ground-based sites is very great. Efforts are now under way to exploit this technique since it is relatively inexpensive. Aircraft have several advantages over balloons in this application: (i) less local contamination of the stratosphere, (ii) manned operation and greater reliability, (iii) recovery of the equipment without damage, and (iv) lower cost per hour of observing.

The problems of atmospheric emission and absorption are largely overcome by operating the telescope in the stratosphere, but much is still to be gained by operating outside the atmosphere in a space vehicle. It is then possible to cool the entire telescope to very low temperatures, thus reducing the background on the detector to arbitrarily low levels. An increase of at least 10 magnitudes over the limiting sensitivity of our present ground-based telescopes is theoretically possible with detectors operated at 0.2°K. At optical wavelengths this difference

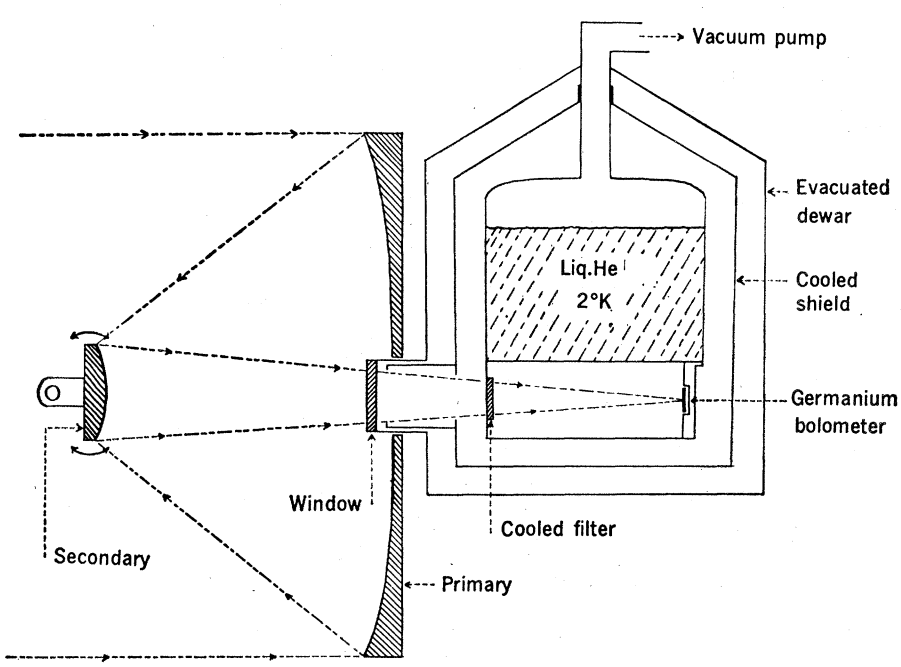

Fig. 1. Principal components of an infrared telescope. The moving secondary mirror modulates the star signal. Only the window and mirrors are uncooled.

is equivalent to the gain associated with the use of the 200-inch telescope instead of a pair of binoculars. In terms of the number of observable sources, we estimate that infrared galaxies alone would be more numerous and detectable at greater distances than normal galaxies as photographed by the 200-inch telescope.

If the foregoing assessment is correct, it would seem that the infrared wavelengths will ultimately play a prominent role in space astronomy. This is contrary to present planning which places the highest priority on the shortest wavelengths.

Infrared Instrumentation

The principal parts of the apparatus depicted in Fig. 1 are a broad-band detector, a cooled interference filter to select the desired wavelength band, a cooled baffle system to limit the field of view, a signal modulator (in this case the secondary mirror and its drive), and the reflecting telescope. Not included are the telescope mounting and associated equipment for finding and tracking the object. This system yields basically only one kind of data —broad-band intensities of small-diameter sources on a relative scale. In those cases where sources of known intensity exist, these relative measures can be converted to absolute fluxes. All of the data given in this paper were obtained in this fashion.

Although this elementary system has found great use, it is lacking in three important respects: (i) it yields only crude information concerning the angular size and structure of sources; (ii) it is nearly insensitive to polarization; and (iii) it cannot resolve spectral details such as emission or absorption lines. Although each of these areas deserves attention, only the last will be discussed further, since it is in the area of spectroscopy that the most significant innovations are taking place.

The method of Fourier transform spectroscopy is fundamental in the infrared region. Connes (*2*) and Hunten (*3*) have reviewed the subject and showed how both the resolution and signal-to-noise ratio of infrared spectra can be greatly enhanced by this technique. In an ordinary spectrometer one or more detectors are used to record each element of the spectrum individually; in the new method all spectral elements are simultaneously recorded on a single detector by using an interferometer to produce the Fourier transform of the whole spectrum. All the energy available from the source is utilized at the expense of increasing the background on the detector; the spectral resolution is not dependent on the image quality or focal length of the telescope. Thus far, the greatest success has been at wavelengths between 1 and 4 microns where the detector noise is independent of the signal and sky noise is nearly absent. In the region from 5 to 25 microns this is not the case, and much work remains before this spectral region is fully developed. Some work has already been done with tunable interference filters which can be cooled to liquid-helium temperatures. As with the Fourier transform spectrometer, the resolution is independent of the focal length and image quality of the optical system. It is not yet clear which approach will be most fruitful. Much depends on the character of the spectra yielded by the various sources, and this is largely unknown.

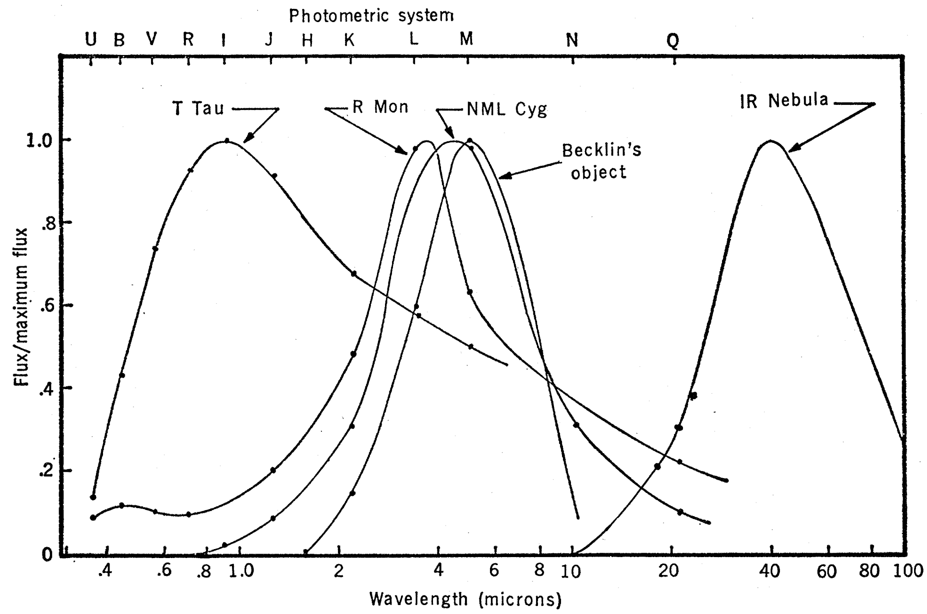

Fig. 2. Normalized spectral energy distributions of five objects representing various stages of stellar evolution. All data were obtained at the University of Arizona on the photometric systems designated by the letters U, B, V, and so forth.

Infrared Stars

Even the coolest of ordinary stars are just less than a third the temperature of the sun, 6000°K; nearly all their energy lies short of 3 microns. From considerations of stability alone, it can be argued that much cooler stars cannot exist for very long. Even in the early stages of contraction when most of the mass of a star is cold and extended, the prospect for a strong infrared source is quite dim since the rate of contraction at this stage is too slow to produce much energy. Nevertheless, luminous infrared stars do exist. The reason is now fairly well understood. Theory predicts that before a star settles onto the main sequence, it undergoes a brief period of very high luminosity at a temperature about equal to the value it will have when it reaches the main sequence. This stage has never been observed optically because the residual cloud of gas and dust in which the protostar is embedded is optically thick. Although little or no visible light can escape directly, the energy is absorbed by the dust and is then dissipated in the infrared region. This mechanism is highly efficient and appears to be chiefly responsible for the bright cool objects that are observed.

Not all bright infrared stars are protostars. The interstellar dust clouds transmit very much like an infrared filter; any object, hot or cold, will appear cold when seen through a dense interstellar cloud. Several excellent illustrations of this type of pseudo-infrared star exist in the Cygnus region where a dense interstellar dust cloud is located at a distance of only a few hundred parsecs.

Figure 2 shows the relative distribution of spectral energy for five infrared objects. It now appears that all these sources are involved in the process of stellar formation. Undoubtedly, the object in Cygnus (*4*) suffers extreme reddening from interstellar extinction since it is in the same dusty region where other heavily reddened stars are found. In addition to the large infrared polarization found by Forbes (*5*), which is consistent with the interstellar reddening deduced by Johnson (*6*), NML Cygnus is associated with a bright OH emission region (*7*), a result which is identical to that for the point source in Orion (*8*). This suggests that a luminous infrared source is involved in the process that produces OH emission. The Orion and Cygnus sources peak at about the same wavelength, but they differ markedly at longer wavelengths. Furthermore, the Cygnus source as a measurable spectrum in the region just short of 1 micron where it resembles a late-type supergiant rather than a premain-sequence object. Clearly, these objects play prominent roles in stellar evolution and their study promises to fill in gaps left by optical astronomy.

If our ideas concerning the cold matter surrounding the luminous infrared stars are correct, we should investigate how this outer part of the protostar influences the subsequent development of the system. The object R Monocerotis has proved enlightening on this point. Low and Smith (*9*) found that the observed distribution in spectral energy (Fig. 2) can be derived from a model in which the circumstellar dust is distributed in the same manner as would be expected if the planets were pulverized and redistributed around the sun at the early stage when the sun's luminosity was as high as that now observed for R Monocerotis. Thus, further study of systems of this type should yield information concerning the formation of planetary systems like our own and provide a new observational basis for cosmogony.

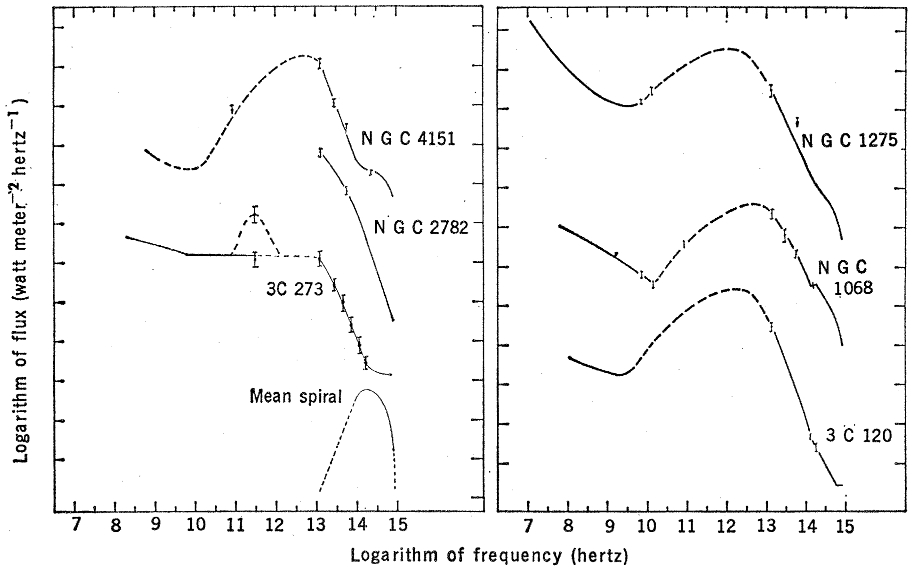

Fig. 3. Spectral flux distributions for various extragalactic objects. Only the infrared data obtained by Low and his collaborators are shown. Only solid portions of the curves are well established. The flux scale in decades has been arbitrarily shifted for each object. The highest flux observed is about 100×10^{-26} watt per square meter per hertz. The quasar 3C 273 is the most distant object; the five galaxies lie between 10 and 100 megaparsecs.

Infrared Nebulas

Even though we now believe that the preplanetary envelope or nebula produces the infrared emission of protostars, the term infrared nebula is reserved for objects which are clearly extended as we view them. At present only a few extended infrared sources are known, and there is some doubt whether some of them are actually resolvable.

A few of the well-known planetary nebulas—objects which are not associated with planets but rather with exploding stars—are strong infrared sources (*10*). An attempt was made to resolve the brightest of these objects, NGC 7027, by use of the 200-inch Hale telescope at 22 microns. The infrared source was found to be much smaller than the visual nebula, less than 5 seconds of arc in diameter. This fact, coupled with the observed distribution of flux at 5, 10, and 22 microns, suggests that we are again dealing with dust heated to a moderate temperature—in this case $\sim 200°K$—by an intense central object of much higher temperature. This model requires the formation of cold dust particles in a hot plasma.

The very cold infrared nebula in Orion was discovered by Low and Kleinmann (*11*) during an attempt to observe the nearby point source discovered by Becklin and Neugebauer (*12*). Recent unpublished measurements based on the use of four different filters between 12 and 25 microns show that the source is indeed a continuum of about 70°K as indicated in Fig. 2 (*13*). Once again we must invoke the idea of a cloud of solid particles heated from within. Even though the temperature is low, the luminosity is so high, $\sim 10^5$ times the sun, that the most plausible source of energy is a cluster of protostars. The proximity of this object to the solar system suggests that it is not unique. This raises the following questions: (i) How many of these systems exist in our galaxy at one time? and (ii) How are they distributed? Fortunately, it should be possible to answer these questions because the interstellar dust clouds which obscure most of our galaxy from direct visual observation are essentially transparent at 22 microns and beyond.

Infrared Galaxies

The first extragalactic infrared source to be studied was the quasar 3C 273B. After detection in 1964 by Johnson (*14*) at 2.2 microns, the observations were extended to all infrared wavelengths available from the ground, including 1000 microns (*15*). The spectral energy distribution of this source is shown in Fig. 3 along with five other extragalactic sources and the mean of several ordinary galaxies (*16*). Details of the observations have been reported (*17*); here let us consider some of their most fundamental implications.

1) A significant fraction of galaxies and quasars radiate more energy into the far-infrared region than all other wavelengths combined.

2) There are nearby galaxies which overlap the quasars in bolometric luminosity when their infrared emission is taken into account. This suggests that quasars, which are relatively rare, simply may be the most highly evolved and luminous members in the class of infrared galaxies.

3) Whatever the nature of the infra-

red galaxy phenomenon, it occurs over an extremely wide range in luminosity, extending at least from less than the luminosity of our galaxy to several thousand times as great a value.

4) The number of infrared galaxies is apparently large enough that the phenomenon must last a large fraction of the lifetime of a galaxy.

5) If the observed rate of energy release lasts for most of the lifetime, then a large fraction of the mass in the nucleus of the infrared galaxy is converted to infrared photons; thus, unlike the usual models for radio galaxies, the mechanism must be highly efficient.

Many of the extraordinary radio and optical phenomena associated with galaxies are thought to be related to explosions in their nucleus. The explosive event releases energy in the form of high-energy particles which then produce the observed "nonthermal" emission by the synchrotron mechanism. The nearby galaxies M82 and M87 display optical evidence of recent explosions in their nuclei (*18*).

A related phenomenon is observed in three of the six infrared galaxies, 3C 273, 3C 120, and NGC 1275, that is, the millimeter and centimeter outbursts which seem to occur every few months. These events appear to be enormously energetic as compared to ordinary supernova, but they are dwarfed by the steady output in the infrared region. Although conditions in the nucleus of the infrared galaxy are certainly favorable for explosions, it does not seem that the explosions themselves can independently account for the quiescent infrared continuum.

The infrared galaxy phenomenon, common to the six objects of Fig. 3, poses challenges to the observer and to the theorist. The observer must use other than ground-based techniques since the peak energy falls between 25 and 1000 microns. The theorist must find an energy source comparable to the rest mass of a galactic nucleus and then explain how this energy is converted almost exclusively into infrared photons.

As we have already seen, the infrared stars and nebulas are important in stellar evolution and cosmogony. The infrared galaxies are at least as important in galactic evolution and cosmology. The apparent fate of at least a few galaxies is that most of their mass is converted into infrared photons. In addition to making these objects detectable at great distances, this should produce a diffuse far-infrared background which can be shown (*19*) to be quite sensitive to models of the universe involving evolution.

If we assume that the physics of the infrared galaxies will be understood eventually and that there is a basic mechanism which can be scaled down from the galactic dimensions on which it is now observed, terrestrial application of this new cosmic energy source may prove more feasible than the current efforts to harness the energy mechanism of stars. The extremely high temperatures of thermonuclear reactions are apparently absent in these sources which radiate at an effective temperature less than that of the earth.

Summary

Advances in detection and instrumentation in the infrared region have greatly expanded the observational capabilities of astronomers. Discoveries of infrared stars and related objects have provided a new opportunity for observing the early stages of stellar evolution and the formative stages of planetary systems like our own. The infrared galaxy phenomenon poses unanswered questions in fundamental physics, reveals new aspects of galactic evolution, may help solve certain parts of the cosmological problem, and could conceivably lead to a new method of energy production.

References and Notes

1. F. J. Low, *J. Opt. Soc. Amer.* **51**, 1300 (1961).
2. P. Connes, *Sci. Amer.* **219** (3), 72 (September 1968).
3. D. M. Hunten, *Science* **162**, 313 (1968).
4. G. Neugebauer, D. E. Martz, R. B. Leighton, *Astrophys. J.* **142**, 399 (1965).
5. F. F. Forbes, *ibid.* **147**, 1226 (1967).
6. H. L. Johnson, *ibid.* **149**, 345 (1967).
7. W. J. Wilson and A. H. Barrett, paper presented at the meeting of the American Astronomical Society, Victoria, B.C., 1968.
8. E. Raimond and B. Eliasson, *Astrophys. J.* **150**, L171 (1967).
9. F. J. Low and B. J. Smith, *Nature* **212**, 675 (1966).
10. F. C. Gillett, F. J. Low, W. A. Stein, *Astrophys. J.* **149**, L97 (1967).
11. F. J. Low and D. E. Kleinmann, *ibid.*, p. L1.
12. J. E. Becklin and G. Neugebauer, *ibid.* **147**, 799 (1967).
13. These data were taken in the winter of 1967–1968. More recent observations show the object to consist of several discrete, extremely cool sources and a surrounding nebulosity. Measurements beyond 25 microns indicate a total luminosity of 10^6 times the sun.
14. H. L. Johnson, *Astrophys. J.* **139**, 1022 (1964).
15. F. J. Low and H. L. Johnson, *ibid.* **141**, 170 (1965); F. J. Low, *ibid.* **142**, 1287 (1965); F. J. Low, in *Highlights of Astronomy*, L. Perek, Ed. (Reidel, Dordrecht, Holland, 1968), p. 136.
16. H. L. Johnson, *Astrophys. J.* **143**, 187 (1966).
17. F. J. Low and D. E. Kleinmann, *Astron. J.*, in press; paper presented at the Conference on Seyfert Galaxies, University of Arizona, Tucson, February 1968.
18. Recent observations by Low and Kleinmann show that M82 can be added to the list of objects which share the infrared galaxy phenomenon.
19. F. J. Low and W. H. Tucker, *Phys. Rev. Lett.*, in press.