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DISCOVERY OF AN INFRARED NEBULA IN ORION

D. E. KLEINMANN

Department of Space Science, Rice University

AND

F. J. Low

Lunar and Planetary Laboratory, University of Arizona, and
Department of Space Science, Rice University*Received June 1, 1967*

Observations at $22\ \mu$ have led to the discovery of an extended source of very low temperature located in the Orion Nebula (NGC 1976) and separated $20''$ from the point source found by Becklin and Neugebauer (1967). This appears to be the first direct observation of an interstellar cloud undergoing rapid contraction and evolution. Presently determined physical parameters are summarized in Table 1. Figure 1 (Plate L1) shows the positions of the two infrared objects as determined by measuring the offsets from $\theta^1(C)$ Ori, the brightest of the Trapezium stars. The measurements for the point source were made at $5\ \mu$; those for the extended source at $22\ \mu$. With a $30''$ beam centered on the infrared nebula, the indicated Q magnitude (Low 1966) is -7.0 , corresponding to a $22\text{-}\mu$ flux density of 5×10^{-15} watt $\text{cm}^{-2}\ \mu^{-1}$, and a brightness temperature of 70°K . At $22\ \mu$ this is the brightest known object outside the solar system!

Scans of the infrared nebula were made with a $13''$ beam, showing a larger extension in right ascension than in declination and a smooth decrease of flux with distance from the center. Until the nebula has been accurately mapped at $22\ \mu$ to determine its structure and total flux, we can give only the flux measured with our largest beam, $30''$ in diameter. Comparison of the fluxes from the two beams and inspection of the declination and right ascension scans indicate that the flux measured by the $30''$ beam is within a factor of 2 of the total flux.

Were the infrared nebula in front of the Orion Nebula it would be seen in Figure 1 (Plate L1) as a dark globule blocking the light from the bright H II region. This is not the case; therefore, the distance must be somewhat greater than the 500 pc taken here for NGC 1976. In projection the centers of the two nebulae are only 0.2 pc apart, implying that their actual separation is not greater than a few parsecs. Therefore, the linear diameter of the central core is about 0.07 pc or 2.3×10^{17} cm.

Direct observations at longer wavelengths are needed to determine the total luminosity and the wavelength dependence of opacity. At shorter wavelengths upper limits have been obtained at 1.6, 2.2, 3.4, and $5.0\ \mu$ by inspection of scans of the region made both at the California Institute of Technology and at the University of Arizona. Our upper limit

L1

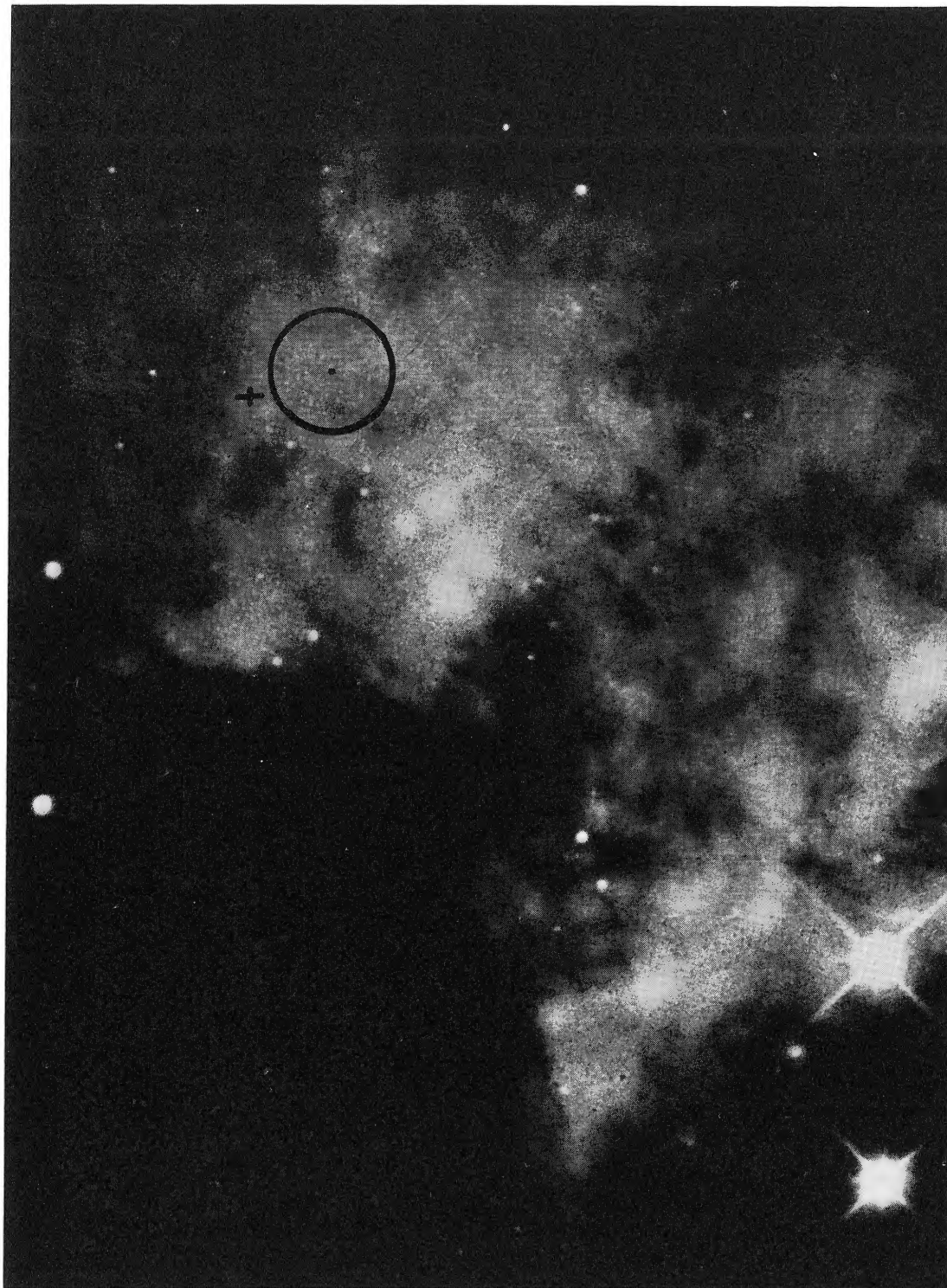


FIG. 1.—A direct photograph of the Trapezium region of the Orion Nebula, indicating the location of the two sources and the surrounding nebulosity. The cross locates the point source, the extent of the lines giving the positional uncertainty. The 30'' diameter circle shows the position of the infrared nebula. The coordinates are given in Table 1.

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at $5\ \mu$ excludes temperatures above 150° K . A much lower upper limit could have been obtained were it not for the high surface brightness of the H II region, about 3×10^{-9} watt $\text{cm}^{-2}\ \mu^{-1}$ sterad $^{-1}$ at $5\ \mu$. This difficulty may also prevent detection of the infrared nebula at radio wavelengths.

In Figure 2 a 70° K Planck curve is plotted to fit the observed flux at $22\ \mu$. If the opacity decreases rapidly with wavelength beyond $22\ \mu$, our black-body extrapolation is in error; however, it can be argued that the opacity of the central part of the nebula remains high and essentially constant over the range of interest, $20\text{--}65\ \mu$. The argument is based on data presented by Gaustad (1963) in his study of the sources of opacity in a contracting interstellar cloud. Gaustad finds that at a temperature of 70° K the opacity is produced by interstellar grains $4 \times 10^{-5}\text{ cm}$ in diameter composed mostly of ices of NH_3 , CH_4 , and H_2O . His tabulation of the absorption cross-section of these grains as a function of wavelength demonstrates the insensitivity of the cross-section to wavelength over the $20\text{--}65\text{-}\mu$ range. From this data we calculate that about $100\ M_\odot$ of gas and dust are required to render the infrared nebula opaque at these wavelengths, while the mass of an interstellar cloud is typically $1000\ M_\odot$.

TABLE 1
PHYSICAL PARAMETERS

	Infrared Nebula	Point Source
$\alpha(1900)$	$5^{\text{h}}30^{\text{m}}19^{\text{s}}.4\ (\pm 0^{\text{s}}.1)$	$5^{\text{h}}30^{\text{m}}19^{\text{s}}.7\ (\pm 0^{\text{s}}.2)$
$\delta(1900)$	$-5^\circ26'38''\ (\pm 3'')$	$-5^\circ26'19''\ (\pm 6'')$
Angular diameter.....	$>30''$	$0''.06$
Magnitude.....	$Q = -7.0\ (30''\text{ beam})$	$M = -0.08\ (13''\text{ beam})$
$22\text{-}\mu$ flux.....	$>5 \times 10^{-16}\text{ watt cm}^{-2}\ \mu^{-1}$	$<1 \times 10^{-16}\text{ watt cm}^{-2}\ \mu^{-1}$
Distance.....	500 pc	500 pc
Linear diameter.....	$2.3 \times 10^{17}\text{ cm}$	$4.8 \times 10^{14}\text{ cm}$
Observed luminosity.....	$3 \times 10^3\ L_\odot$	$1.4 \times 10^3\ L_\odot$
Total luminosity.....	$>1 \times 10^5\ L_\odot$	$1.4 \times 10^3\ L_\odot$
Effective temperature.....	$\sim 70^\circ\text{ K}$	$\sim 610^\circ\text{ K}$
Mass.....	$10^2\text{--}10^3\ M_\odot$	?
Lifetime.....	$\geq 2 \times 10^3\text{ years}$	?

It follows from the above that the effective temperature is 70° K and the luminosity is

$$L = 4\pi\sigma T_e^4 R^2 \approx 1 \times 10^5 L_\odot ,$$

or 4×10^{38} ergs/sec. In the most extreme case possible all the energy is radiated within the $17.5\text{--}25\text{-}\mu$ band of our photometer, resulting in a luminosity down by a factor of 30 from the above estimate. The luminosity may be appreciably greater than $10^5\ L_\odot$ if, as suggested by Gould (1964), much of the energy is radiated in the $28\text{-}\mu$ line of H_2 .

Gravitational contraction of the body as a whole cannot produce energy at a sufficient rate unless the mass is unreasonably large. Both Cameron (1967) and Hartmann (1967) have, therefore, considered models in which stars have already begun to form near the center.

The point source discovered by Becklin and Neugebauer is undetectable at $22\ \mu$, but has been observed to have an M magnitude of -0.08 . Its flux is plotted in Figure 2; for comparison the very hot Trapezium stars, M magnitude $+2.78$, have also been plotted. Neglecting interstellar extinction of the shorter wavelengths but including the new measurement at $5\ \mu$, the luminosity of the point source is $1.4 \times 10^3\ L_\odot$. This is comparable to that found for R Mon (Low and Smith 1966), although the spectral energy

distributions of the two protostars are quite different. The rapid decrease in flux beyond $5\ \mu$ is difficult to understand, and it is uncertain whether this object is part of the infrared nebula or the Orion Nebula since individual stars can be forming in either.

The discovery of the infrared nebula in Orion means that the early stages of star and star-cluster formation can be observed in the far infrared. The signal to noise ratio obtained at $22\ \mu$ with a 28-inch telescope, where the object completely filled the $30''$ beam, was on the order of 10^3 . This result and the transparency of the interstellar medium at $22\ \mu$ imply that any other similar galactic objects would also be detectable. The fact that the first of these objects to be found is so close to the Sun suggests that a large family of related objects may exist throughout the Galaxy. However, current ideas concerning O

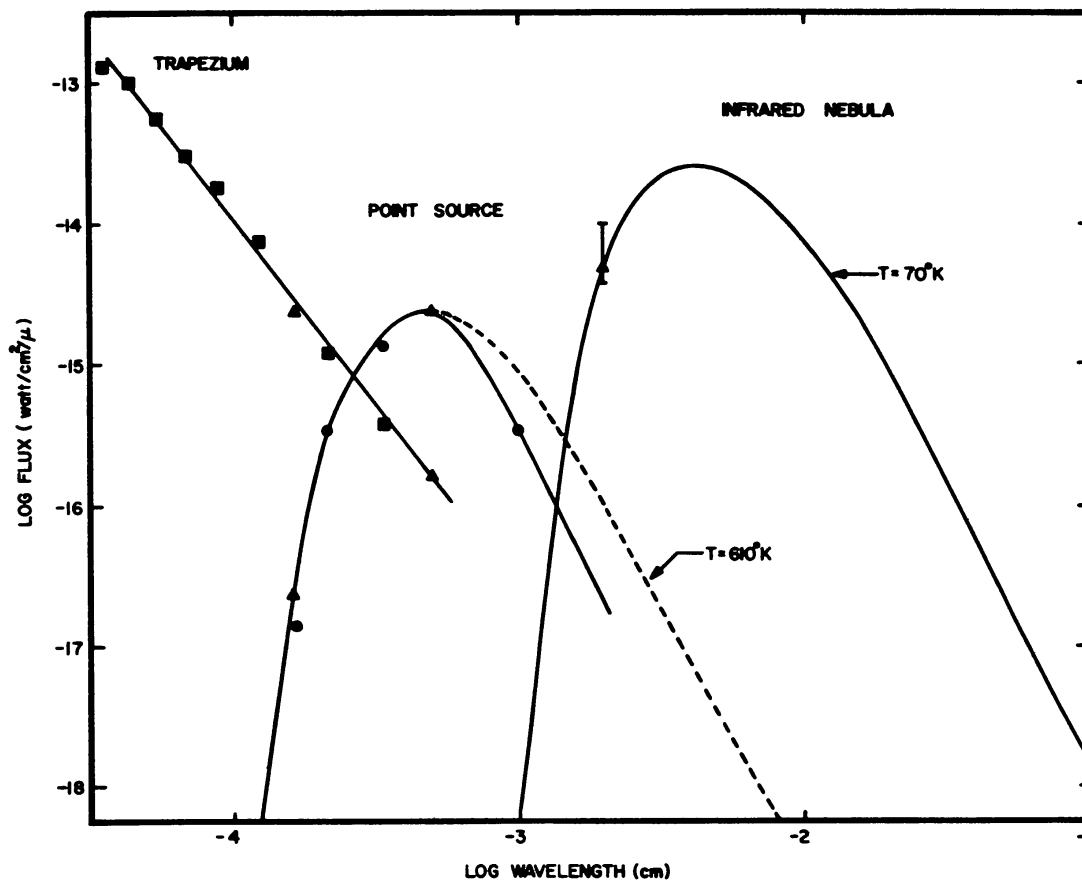


FIG. 2.—Observed flux versus wavelength for the Trapezium stars, the point source, and the infrared nebula. The squares indicate data taken from Johnson, Mitchell, Iriarte, and Wisniewski (1966). The circles are data presented by Becklin and Neugebauer (1967). The triangles are data obtained by the authors.

stars and associated clusters (Sharpless 1965) indicate a maximum rate of formation of about one per 200 years. The lifetime of the infrared phase of these objects could be as short at 2000 years, implying that there may be only ten such objects in the Galaxy. If further observations show a high space density, suggested by our proximity to the infrared nebula in Orion, then the time scale on which these objects are formed must be substantially lengthened. This time scale question and other fundamental problems concerning the earliest stages of stellar evolution can now be answered by direct observation.

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Note added in proof: By offsetting from $\theta^1(\text{C})$ Ori and θ^2 Ori with their $2.2\text{-}\mu$ photometer on the 200-inch Hale telescope, Becklin and Neugebauer (private communication) have recently obtained a more accurate position for the point source. Their 1900 coordinates are $\alpha = 5^{\text{h}}30^{\text{m}}19^{\text{s}}.4 (\pm 0^{\text{s}}.1)$ and $\delta = -5^{\circ}26'21'' (\pm 1'')$.

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