INFRARED OBSERVATIONS OF POSSIBLE PROTOSTARS

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In the past four years, many objects which radiate 80 percent or more of their energy at wavelengths longer than 2μ have been found at the University of Arizona and by the infrared group at Caltech. Of these infrared objects, most are probably not protostars. However, several infrared objects have been found within HII regions and gaseous nebulae, and therefore it is natural to assume that these objects could be protostars. Without going into the theoretical question of whether a protostar of a certain type can exist or not we would like to describe the observational data on three of these objects.

The first of the infrared objects which could be a protostar is R. Monocerotis; it is situated at the head of Hubbell's variable nebula, NGC-2261, which is not an HII region. E. Mendoza V. (1966) found that, as well as having a visual component which is classified as a T-Tauri star, R Mon radiates most of its energy beyond 2μ. T-Tauri stars are known to be among the youngest stars in the galaxy, so we already have a connection between infrared radiation and young stars. The measured energy distribution of R Mon is shown in Figure 1. It is seen that there is a peak around 4μ which corresponds to a black body temperature of 750°, and also that there is a peak in the visual from which its identification as a T-Tauri star comes. The flux density at 22μ has been measured by Low (Low and Smith, 1966). He finds an excess of radiation at 22μ with respect to what one would expect from an 750^{0} black body. Low and Smith (1966) have interpreted this in terms of a circum-stellar dust cloud around the star which absorbs the optical radiation and reemits the radiation at the longer infrared wavelengths; they suggest this could be evidence of a preplanetary system.

The total luminosity of R Mon, if it is at the distance of the cluster NGC-2264 is 10^{3} $L_{\odot}$. It should be pointed out that the measured infrared excess of R Mon cannot be explained completely through interstellar absorption, although many of the infrared stars have been explained in this way. Mendoza (1966) has measured many T-Tauri stars and finds that they all have infrared excess in their radiation, although none as extreme as R Mon.

An object quite similar to R Mon is a point source of infrared radiation that was discovered (Becklin and Neugebauer, 1967) in the Orion Nebula while systematically scanning the nebula at 2.2μ using the 60-inch optical telescope at Mount Wilson and an aperture of 13". Interest in this object has increased in the last few months since Raimond and Eliason (1967) have tentatively identified the OH emission in the Orion Nebula to be coincident with this point source to within a matter of a few seconds of arc. Unlike R Mon, the point source in the Orion Nebula is not associated with a visual object. There have been two charts of this source in the literature, one by Becklin and Neugebauer (1967) and one by Kleinmann and Low (1967), and neither is very accurate. Figure 2 shows the correct position of the source in the Orion Nebula.

The coordinates of the point source were measured on the 200-inch Hale telescope by off-setting from both θ_2 and from θ_1(C) in the trapezium; the 1950 coordinates are:

$$\alpha = 5^h\ 32^m\ 46.7^1 \pm 0.1^s$$

$$\delta = -5^o\ 24'\ 17'' \pm\ 1''$$

Figure 3 shows the energy distribution of the point source including a measurement by Kleinmann and Low (1967) at 5μ. The peak around 4 or 5μ corresponds to a black body temperature of approximately 650^{o}K, but the agreement with a black body is poor. In contrast to the case of R Mon, where an excess appears at 20μ, the Orion source apparently has an excess around 5μ. The deviations at 5μ could be due to variability, although there is evidence that this is not the case. In Table I we list the Caltech measurements on the source at 2μ; the April 1967 measurement was made at approximately the same time that Kleinmann and Low were making the 5μ measurement. Another possible explanation for the 5μ excess is line emission near 5 and 3μ, but no spectral scans have been obtained yet. It is of some interest that on a good print taken in the near infrared, there is a slight indication that there might be some emission in the region; if this is confirmed, the energy might be similar to that of R Mon. The total luminosity of the star, assuming that it is at the Orion Nebula and neglecting any absorption which would be present, is $10^3\ L_\odot$; the properties of R Mon and the Orion point source are thus quite similar. If the source radiates as a black body at this temperature, its radius would be about 10 Au or .03". The highest resolving power used has been 2" which is so much larger than .03" that no test of these arguments has been made.

It is possible that the source is a highly reddened super giant, situated behind or in the nebula. In that case there would be 30 to 40 magnitudes of visual absorption needed. It cannot be an O-type star unless the visual magnitude is brighter than -10. If moderate to high amounts of absorption (eg., $A_V = 10$) are assumed, the temperature of the object only goes up to about $1000^{o}K$, which is not an appreciable change.

In April of this past year Kleinmann and Low (1967) attempted to measure the point source at 20μ; they were unable to make the measurement because of the presence of a large source of extended radiation around the region. The position of the extended source as given by Kleinmann and Low (1967) is included in Figure 2.

The observations at 20μ show that the nebula has the following properties. The flux density at 20μ is 10^{-22} watts/m^2 hz, or 10^4 flux units. It corresponds to a 20μ magnitude of -7, and as such is the brightest object in the sky at 20μ outside the solar system; in fact, it is the brightest object other than the Moon and the Sun as observed from the earth. The observed luminosity of this extended source is 3×10^3 $L_{\odot}$, while its linear diameter is 2×10^{17} cm. The brightness temperature is $70^{o}K$. Information on the color temperature is not available, but one can get an upper limit on the temperature from the 5μ measurements that Kleinmann and Low have made in the nebula, and one finds that the color temperature is less that 150°K. It has been shown by Hartman (1967) that the gravitational contraction of a body as a whole cannot produce the energy apparently present at a sufficient rate unless the mass is larger than 10^4 $M_\odot$. Thus the present interpretation of the source is that it is a very dense cloud in which young O and B stars have formed. The cloud would be optically thick at 20μ and also in the visible.

A systematic search for infrared sources fainter than K = 2.2μ been made for only one HII region, namely the Orion Nebula. A natural question to ask is if one could observe sources in other nebulae if they do exist. If one assumes the use of a 60-inch telescope, and would like to scan a 4' by 4' region, like the Orion Nebula, in one or two nights of observing, one could observe with current techniques down to a 2.2μ magnitude of approximately 8, a 3.4μ magnitude of approximately 5, and a 5μ magnitude of approximately 2. These limits are all approximately 10 times fainter than the point source in Orion, so similar sources could be seen to a distance of approximately 1.5 kpc; this certainly would include many more HII regions, including some of the compact HII regions recently discovered by Mezger, Altenhoff, Schraml, Burke, Reifenstein, and Wilson (1968). If one were to observe on the 200-inch, one could detect sources out to 5 kiloparsecs. With respect to finding extended sources at longer wavelengths, Low (1967) has estimated that with a ground based survey one could find sources a factor of 10 fainter than the Orion extended source. Thus we are limited to a region of around 1.5 kiloparsecs. However, Low is now planning to carry out an air-borne survey at 20μ in which case he may be able to increase the distance to which he can work.

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TABLE I

K Magnitude of the Orion Point Source

Date	K(2.2μ) Magnitude
January 20, 1965	5.0 ± 0.2
April 4, 1966	5.2 ± 0.1
April 8, 1967	5.3 ± 0.2
December 16, 1967	5.0 ± 0.2

Figure Captions

Figure 1 The energy spectrum of R Mon, the Sun and T Tauri (Mendoza, 1966; Low and Smith, 1966).

Figure 2 The area of Orion surrounding the infrared point source and extended source. The chart is made from star positions given by Parenago (1954).

Figure 3 The energy spectrum of the infrared point source in Orion. The measurement at 5μ is by Kleinmann and Low (1967), the rest are by Becklin and Neugebauer (1967).

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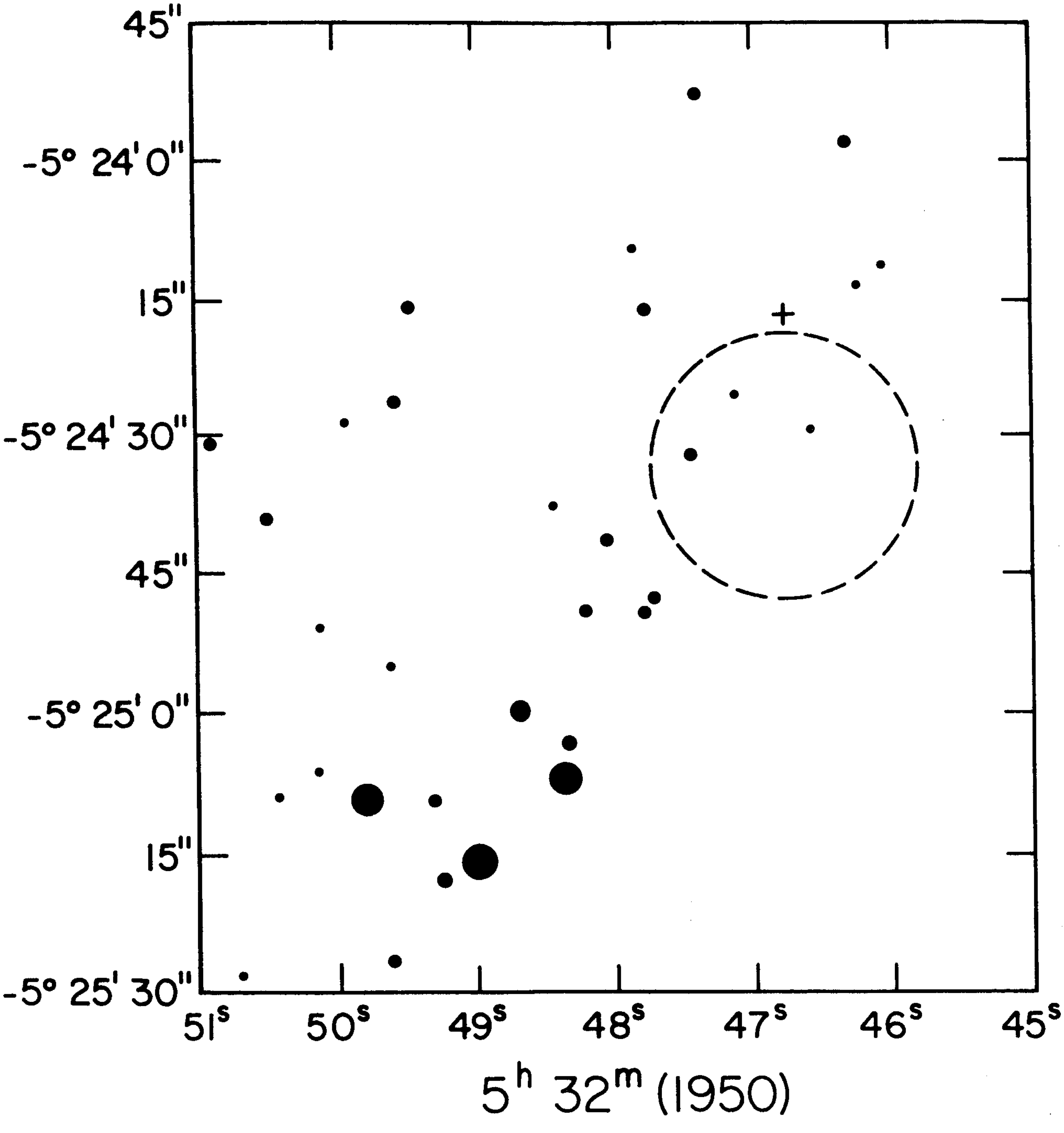
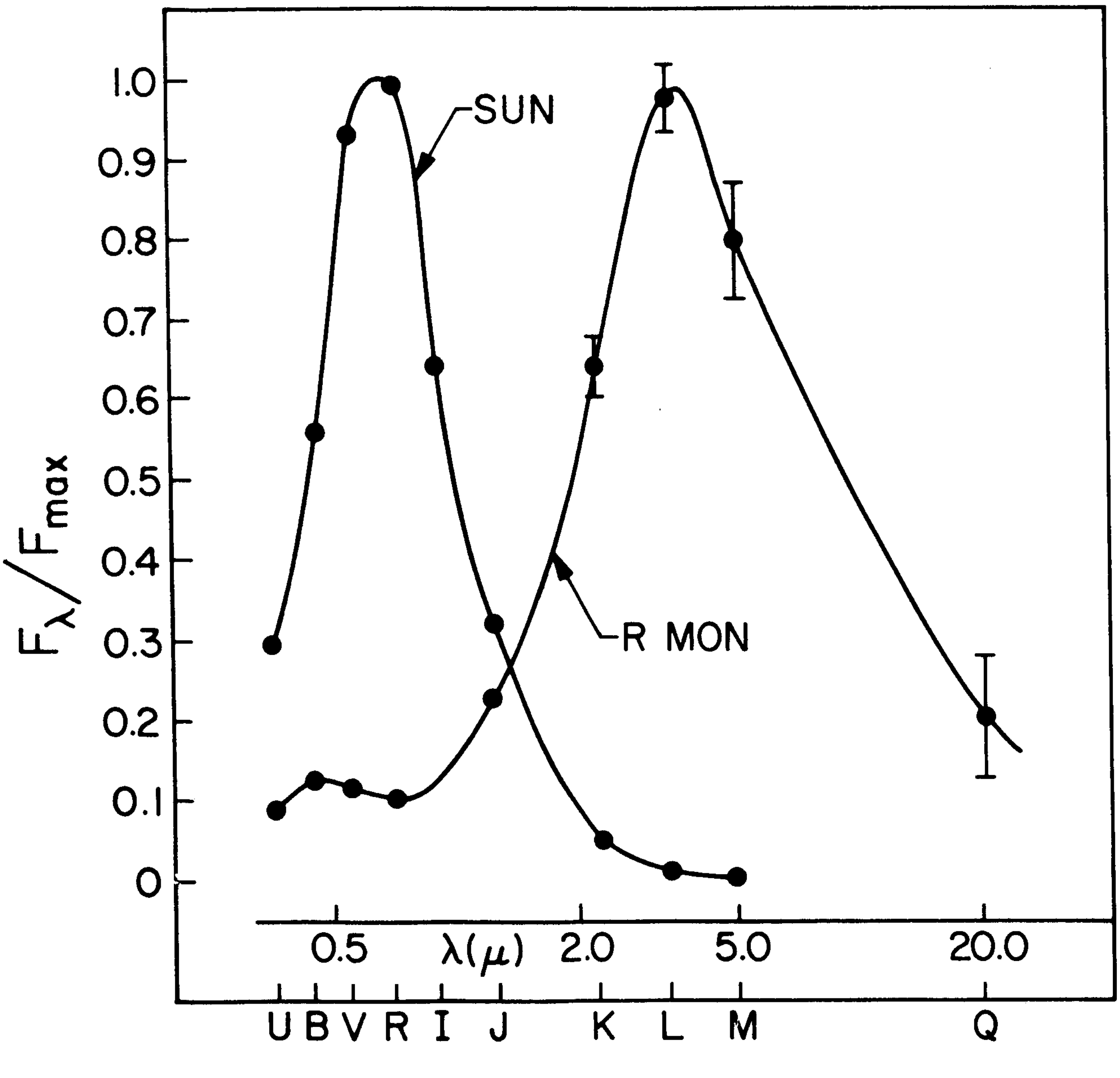


45''
-5° 24' 0''
15''
-5° 24' 30''
45''
-5° 25' 0''
15''
-5° 25' 30''
51s
50s
49s
48s
47s
46s
45s
5h 32m (1950)

Figure 1



F_λ / F_{max}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SUN
R MON
0.5
$\lambda(\mu)$
2.0
5.0
20.0
U B V R I J K L M Q

Figure 2

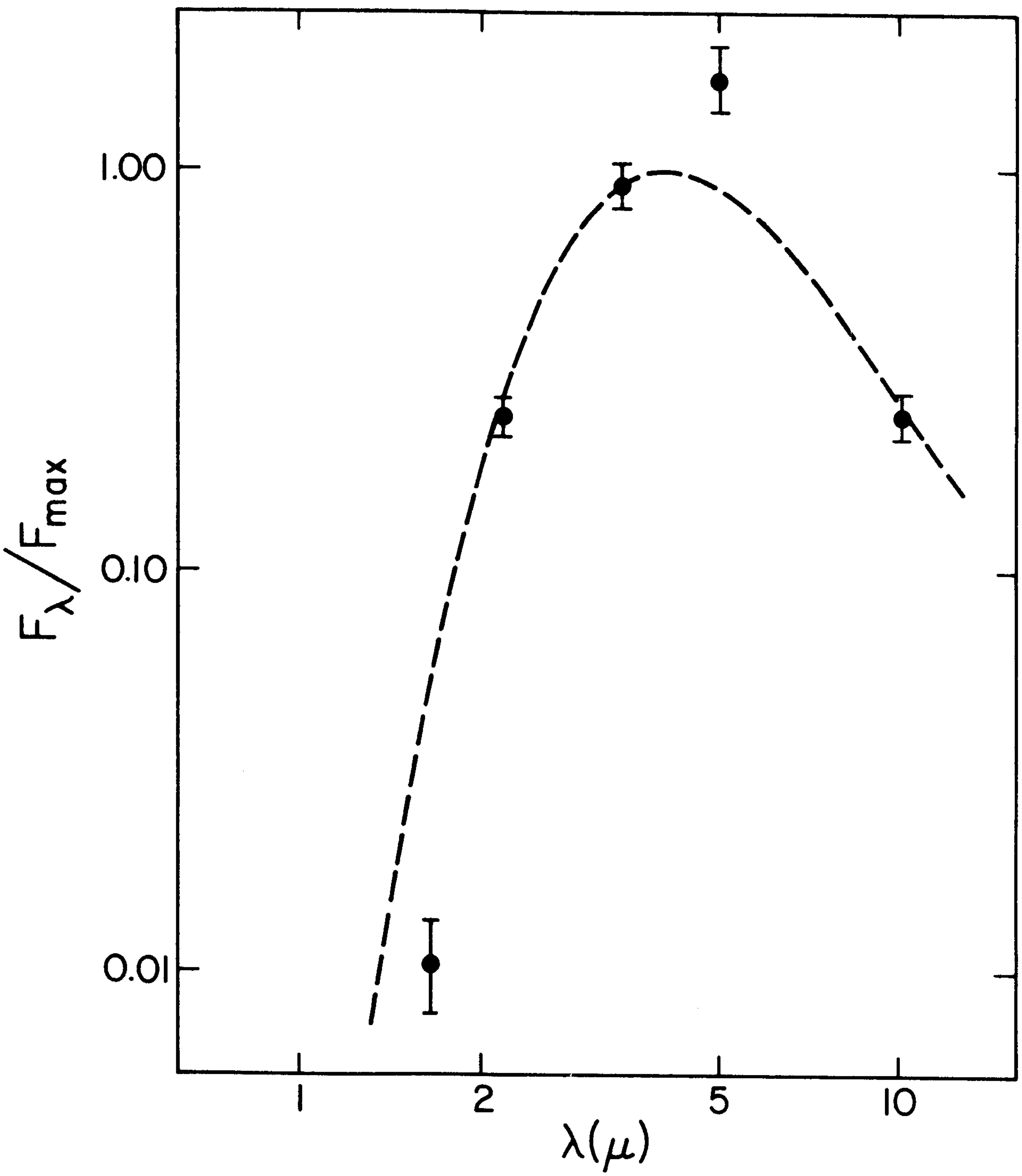


Figure 3