No. 138 INFRARED OBSERVATIONS OF A PREPLANETARY SYSTEM*

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ABSTRACT

R Monocerotis and other similar infra-red emitting objects are viewed as proto-planetary systems consisting of a contracting central star and surrounding dust envelope.

R Monocerotis, the twelfth magnitude object at the head of Hubble's Variable Nebula, is classified as a *T* Tauri variable — a type of star thought to be in the latter stages of contraction. Mendoza's (1966) infrared observations showed an unexpectedly large infrared excess for *R* Monocerotis, which he suggested might be caused by an infrared companion. We have extended the infrared observations to a wavelength of 20 μ, finding excellent agreement with a model in which thick circumstellar dust absorbs and re-radiates the energy produced by a luminous central object. The high luminosity found for the system is consistent with the idea that *R* Monocerotis is a protostar still undergoing contraction. If this is the case, both the energy released in the contraction and most of the angular momentum are being transferred to an extended envelope of dust which will ultimately form a planetary system around the star.

The 20 μ flux density and estimated probable error are given in Table 1 for *R* Monocerotis, *T* Tauri and *NML* Cygnus. Absolute fluxes may be computed for shorter wavelengths using Johnson's (1965) calibration and either Mendoza's (1966) magnitudes for *R* Monocerotis and *T* Tauri, or the results of Johnson, Low and Steinmetz (1965) for the Neugebauer, Martz and Leighton (1965) infrared star in Cygnus. The new flux for *NML* Cygnus at 20 μ is based on further observations and a more accurate calibration procedure which will be discussed elsewhere.

TABLE 1

OBJECT	FLUX DENSITY ($W/cm^2/\mu$)	PROBABLE ERROR
R Monocerotis	$1 \cdot 0 \times 10^{-16}$	$0 \cdot 2 \times 10^{-16}$
T Tauri	$0 \cdot 37 \times 10^{-16}$	$0 \cdot 2 \times 10^{-16}$
NML Cygnus	44×10^{-16}	6×10^{-16}

Fig. 1 shows the remarkable agreement between our observed flux from *R* Monocerotis at 20 μ and the spectral energy distribution computed for the dust model. For comparison, a Planck distribution has been fitted to the peak at $3 \cdot 4$ μ. Curve *C* represents the spectral energy distribution of a solar type star normalized to give the total output of the system. This is approximately what we would expect to find if the circumstellar dust were suddenly removed. Some of this light filters through the dust to

*Reprinted from *Nature*, Vol. 212, No. 5063, pp. 675–676, November 12, 1966.

produce the observed U.B.V.R.I. magnitudes and the optical spectrum on which the classification Ge (Joy 1960) of the central object is based.

From the flux observed at V ($0 \cdot 5\ \mu$) and curve C, which reaches a peak near V at a value of 110×10^{-16} W/cm$^2/\mu$, we find the visual transmission of the dust to be $0 \cdot 6$ per cent. The total flux received at the Earth, 6×10^{-15} W/cm^2, was obtained by integrating the spectral energy distribution from $0\ \mu$ to $40\ \mu$. Only a small error is made by neglecting the energy beyond the range of validity of curve C. Assuming the source is isotropic and that it is located in *NGC* 2264, we calculated its luminosity as 870 times that of the Sun, using the distance of 690 parsec (corrected for interstellar extinction, Johnson 1968). Hayashi (1966) has shown that a protostar of one solar mass would reach this peak luminosity at about the temperature (6,000° K) determined from the optical spectrum of *R* Monocerotis.

The dust surrounding a protostar is undoubtedly confined mostly to a disk perpendicular to the axis of rotation, but for simplicity we consider a spherically symmetric system. Spherical dust particles are assumed with density, n, varying with particle radius, a, and distance from the star, r, according to the relation

$$n(a,r) = C\, a^{-p}(D/r)^{\alpha} \qquad (1)$$

where C is the density of unit particles at 1 a.u. (D) and α and p are dimensionless parameters. The relation was used by Ingham (1961) to describe the zodiacal light by adjusting C, α and p to fit the optical data. α was found to lie between $1 \cdot 0$ and $1 \cdot 5$, and p was 4 or 5. The minimum particle radius, a_0, is not known because it depends on several conflicting processes. Fortunately, it is not critical in our analysis. The minimum radial distance, r_0, is important and can be related to the vaporization temperature, T_v, of the particles. For optically thin dust, we can write the temperature as

$$T(r) = L^{1/4}\, T_e\, (D/r)^{1/2} \qquad (2)$$

where L is the luminosity and T_e is the temperature of a particle at a distance of 1 a.u. from the Sun. T_e depends on the particle albedo and will be taken here to be 266° K.

If we assume the particles radiate independently of their size, we can write the differential thermal flux for a thin spherical shell as

$$\mathrm{d}I(a,r,\lambda) = n(a,r)B(\lambda,r)\,(4\pi a^2)\,(4\pi r^2)\mathrm{d}a\,\mathrm{d}r\,\mathrm{d}\lambda \qquad (3)$$

The brightness spectrum of a particle can be approximated by the Wien law

$$B(\lambda,r) = \frac{2\pi hc^2}{\lambda^5} \exp\left(\frac{-hc}{\lambda k\, T(r)}\right) \qquad (4)$$

Substitution of (1), (2) and (4) in (3) provides an equation which can be integrated. We take p equal to 5, so that the total mass of dust is finite, and choose $1 \cdot 1$ as the value of α. Integrating a from a_0 to ∞ and r from r_0 to ∞, we have to a good approximation

$$\begin{aligned} \mathrm{d}I(\lambda) = c_1 \exp(-c_3/\lambda)\,[c_2 r_0^{1.4}\lambda^{-4} + \\ 2 \cdot 8\, c_2^2\, r_0^{0.9}\, \gamma^{-3} + 5 \cdot 04\, c_2^3 r_0^4 \lambda^{-2} + \\ 4 \cdot 06\, c_3^4 r_0^{-0.1}\, \lambda^{-1}]\mathrm{d}\lambda,\ (0 < \lambda < 10_\mu) \end{aligned} \qquad (5a)$$

$$\mathrm{d}I(\lambda) = c_1 c_2^{3.8}\, \Gamma(3 \cdot 8)\lambda^{-1.2},\ (10_\mu < \lambda < 40_\mu) \qquad (5b)$$

where

$$\begin{aligned} c_1 &= 32\pi^3\, \mathrm{CD}^{1.1}\, \mathrm{a}_0^{-2} hc^2 L^{0.95} \\ c_2 &= kT_e\, D^{0.5}/hc \\ c_3 &= r_0^{0.5}\, c_2^{-1} \end{aligned}$$

From this result it can be seen that the value of r_0 determined by T_v in equation (2) sets the peak wavelength, and that the value chosen for α controls the shape of the distribution. C, L, a_0 and p merely influence the strength of the source.

It is instructive to consider the solar system. Under the assumptions made here, and where C is derived from Ingham's model as $3 \cdot 8 \times 10^{-30}$/cm^3 and T_v is taken as 1,385° K, the relative brightness at $5\ \mu$ of zodiacal dust emission to the Sun itself is $2 \cdot 0 \times 10^{-6}$. If the density C in equation (1) were increased by a factor of $5 \cdot 0 \times 10^5$ this ratio would become unity and the extinction at V caused by interplanetary dust would be only 0.045 magnitudes. This situation must have occurred early in the formation of the solar system.

In the case of *R* Monocerotis, the dust is much thicker but, as Fig. 1 shows, our model fits the data extremely well if α equals $1 \cdot 1$ and T_v is 1,385° K. The hottest shells of dust are partly obscured by cooler layers, and therefore the temperature 1,385° K is probably too low. Graphite particles are thus not to be ruled out completely as a main constituent, but other components should be considered, and ice, at least, is not predominant.

As a consequence of our model, the diameter of the object varies roughly as the square of the wavelength. The linear diameter at $20\ \mu$ is computed to be about 200 a.u., implying an angular diameter of $0 \cdot 14$ sec of arc. Thus an important test of this dust

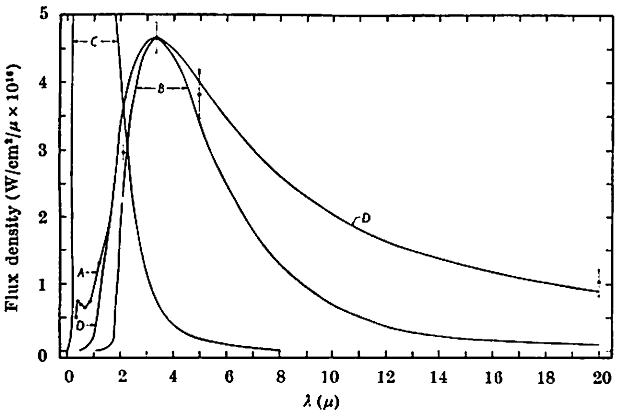

Fig. 1 The absolute spectral energy distribution. Curve *A* is drawn through the U.B.V.R.I.J. observations. The long wavelength observations are shown with their error bars. Curve *B* is an 850° K Planck distribution fitted to the peak. Curve *C* represents part of a distribution for a solar type star normalized to the same total intensity as *R* Monocerotis; the peak flux of 110×10^{-16} W/cm²/μ occurs at 0·43 μ. Curve *D* represents the dust model normalized to the observation at 3·4 μ.

model is the measurement of angular size and brightness distribution at long wavelengths.

The minimum particle radius was assumed to be 10 μ in order to estimate the total mass. No effects of particle size are found to a wavelength of 20 μ, and thus this is perhaps reasonable. Based on the visible extinction, the total mass of dust is $6{\cdot}3 \times 10^{29}$ g or 3×10^{-4} solar mass. This is equal to about 0·25 of the mass of our planetary system; however, it is perhaps only 0·01 of the uncondensed gases, mostly hydrogen. It is well known that angular momentum considerations require a large circumstellar mass of this order.

Other *T* Tauri stars may be in various stages of contraction, have different amounts of dust and be seen in a variety of projections, but should be sufficiently similar to *R* Monocerotis to be treated in much the same fashion. The flux found at 20 μ for *T* Tauri itself, if correct, indicates that the effects of particle size may be significant. A case of special interest is the brightest of the known infrared stars, NML Cygnus. Here we also find more radiation at a long wavelength than is usual, which suggests an increase of diameter with wavelength. If it is a system like *R* Monocerotis, then its dust envelope is much thicker because no visible light is detected. The total flux received at the Earth is $4{\cdot}3 \times 10^{-13}$ W/cm² resulting in a distance of 80 pc. if its luminosity equals that of *R* Monocerotis. Its angular size would, therefore, be 1·2 sec of arc, within the resolving power of the largest telescope which can be used at 20 μ. Johnson (1966a) has postulated that *NML* Cygnus is a highly reddened *M6Ia* star. In that event, the angular diameter would be about 0·1 sec of arc independent of wavelength.

Additional flux density measurements for *R* Monocerotis and related objects should reveal further details concerning the high luminosity phase of protostar evolution, the formation of circumstellar dust and the development of planetary systems. In particular, the observations should be extended to longer wavelengths to investigate particle size effects. Radio observations (Johnson 1966b) of the *R* Monocerotics–*NGC* 2261 system have all given negative results, including a recent observation (Hogg 1966) at 1·9 cm with the 140 ft. telescope at the National Radio Astronomy Observatory. Infrared spectroscopy may reveal molecular absorption features (NH_4, CH_4, H_2O, CO_2, etc.) just as in the planets but, because of the low pressure, the lines should be quite narrow. In addition to the study of brightness distribution as a function of wavelength already emphasized, there should be detectable transient phenomena following rapid changes in the luminosity of the central object.

Acknowledgments. This work was supported by grants from the U.S. National Science Foundation and the National Aeronautics and Space Administration.

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