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INFRARED REFLECTION NEBULAE AROUND GL 490 AND R MONOCEROTIS: SHELL STRUCTURE AND POSSIBLE LARGE DUST GRAINS

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ABSTRACT

We present K band images around GL 490 and R Mon. Both maps show that a curved ridge encloses a dim region in an infrared reflection nebula. This ridge is created by scattering from a dense shell of material and can be directly observed in the near-infrared because the optical depth is small. R Mon also shows an extension perpendicular to that of the infrared reflection nebula. We believe that this feature arises from scattering by dust in the disk because of the spatial coincidence with the molecular disk. The column densities in the shell around R Mon calculated using a dust model derived for interstellar dust are about an order of magnitude larger than that expected from radio molecular line observations. This discrepancy can be resolved if we assume large dust grains in this star-forming region.

Subject headings: infrared: sources — interstellar: grains — nebulae: individual (GL 490, R Mon) — nebulae: reflection

I. INTRODUCTION

Many infrared sources in star-forming regions are associated with diffuse near-infrared nebulae. Most of the radiation from these nebulae is considered to be scattered light from the central star because of the centrosymmetric pattern of the polarization vectors; these are infrared reflection nebulae (e.g., Werner, Dinerstein, and Capps 1983; Heckert and Zeilik 1984; Lenzen, Hodapp, and Solf 1984; Castelaz *et al.* 1985; Yamashita *et al.* 1987*a*; Yamashita *et al.* 1988). They are frequently associated with CO bipolar flows and their extension coincides with blueshifted lobes of the bipolar flows (e.g., Cep A: Lenzen, Hodapp, and Solf 1984; Rodriguez, Ho, and Moran 1980; L1551: Nagata *et al.* 1986, Snell, Loren, and Plambeck 1980). This suggests that the structure of infrared reflection nebulae is dictated by bipolar flows.

Recently high spatial resolution CO observations of the L1551 bipolar flow revealed a shell structure (Snell and Schloerb 1985; Uchida *et al.* 1987). Yamashita *et al.* (1987*a*) showed that an infrared reflection nebula, GGD 27 IRS (also a CO bipolar flow source; Yamashita *et al.* 1989), arose from scattering at the surface of a cavity. We might expect that shell structure should commonly be seen as a ridge in surface brightness maps. Visual and infrared maps of many infrared sources presented so far have, however, showed no shell structures (L1551 IRS 5: Mundt and Fried 1983; GL 490: Campbell, Persson, and McGregor 1986; R Mon: Aspin, McLean, and Coyne 1985 [at visual wavelengths]; Cep A: Lenzen, Hodapp, and Solf 1984; GSS 30: Castelaz *et al.* 1985; GGD 27 IRS: Yamashita *et al.* 1987*a*; GL 2591: Yamashita *et al.* 1987*b* [at infrared wavelengths]).

The absence of shell structure might be attributed to low spatial resolution in some cases and to inclination effects in others, but the main reason may be optical depth. Therefore we planned to make near-infrared maps of sources expected to be optically thin in the near-infrared. We selected R Mon and GL 490 as targets because they show relatively small K band polarization (4.6% for R Mon and 7.0% for GL 490; Sato *et al.* 1985) among typical bipolar molecular flow sources. We believe in these two cases that the polarization is diluted by direct emission from the central sources because the density is low, although some effect due to inclination may be present. The low optical depth also allows us to discuss grain properties, because the resultant relationship between surface brightness and scattering coefficient of the grains is simple.

II. OBSERVATIONS AND RESULTS

We made photometric maps of GL 490 and R Mon in the K band on the 3.8 m United Kingdom Infrared Telescope (UKIRT) on 1986 January 15 and 1987 January 15, respectively. We used the UKIRT photometer UKT9 which is equipped with a single InSb detector cooled by solid nitrogen. Polarimetric measurements were made using Kyoto polarimeter in conjunction with UKT 9 on 1987 January 21 and 1988 April 30.

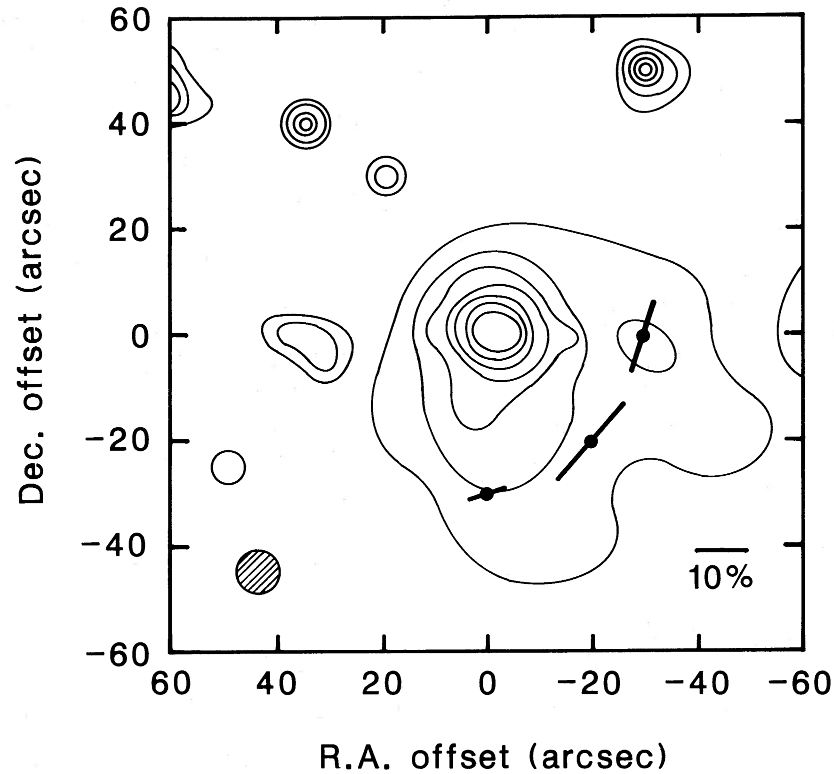

FIG. 1.—A K band surface brightness map around GL 490. The map center is R.A.(1950) = $3^h23^m38^s.9$, decl.(1950) = 58°36′33″. Contour levels are 0.5, 1, 2, 5, 10, 20, 50 × 10^{-20} W cm^{-2} μm^{-1} $arcsec^{-2}$, respectively. The contours in the vicinity of GL 490 are dimmed for the purpose of simplicity. Three thick bars indicate the direction and the degree of polarization in the K band at the position of their center indicated by the filled circles. The beam size of 8″ is indicated by the hatched circle in the left lower corner, and the polarization degree of 10% is shown in the right lower corner.

Mapping observations were made with an aperture of 8″ and a grid spacing of 5″. GL 490 was mapped using a DC method with a sky measurement at 350″ north of GL 490 every 25 map positions. R Mon was mapped using a standard AC method with a chopping throw of 220″ in the E-W direction. Sky offset was monitored at 600″ east of R Mon every 50 map positions. Flux calibration was achieved by observations of HD 106965. The resultant maps are displayed in Figures 1 and 2. Signal-to-noise ratios per pixel are about 3 at the lowest contours for both sources. The relative positional accuracy within the maps was measured to be less than 1″ by monitoring a field star every sky measurement.

Polarimetric observations were made on three positions around GL 490 and R Mon with an aperture of 20″ and a chopping throw of 220″ in the E-W direction. The position angles were calibrated using L1551 IRS 5 (161° in the K band; Nagata, Sato, and Kobayashi 1983) and GL 2591 (171° in the K band; Lonsdale *et al.* 1980). The resultant polarizations are summarized in Table 1 and displayed in Figures 1 and 2.

III. DISCUSSION

a) The Shell Structure and the Disk

Figures 1 and 2 show that both GL 490 and R Mon are associated with diffuse emissions extending for about 1′ from the central sources. These diffuse emissions are most likely understood as reflection nebulae; thermal emission by dust in equilibrium with stellar radiation is excluded because of the low temperature (100 K ∼ 150 K) of the dust at the distance of

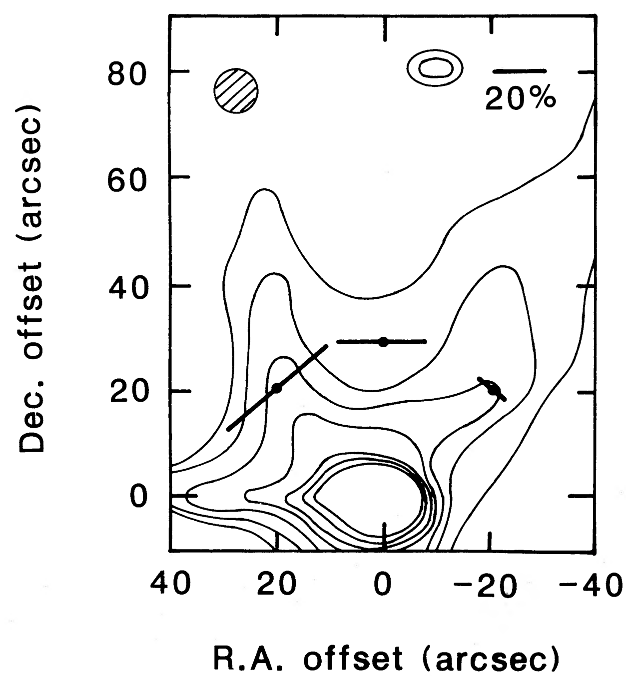

FIG. 2.—A K band surface brightness map around R Mon. The map center is R.A.(1950) = $6^h36^m25^s.3$, decl.(1950) = 8°48′00″. Designations are the same as Fig. 1, except for the contour levels of 0.4, 0.8, 1.5, 3, 5, 10, 20 × 10^{-20} W cm^{-2} μm^{-1} $arcsec^{-2}$ and the length of the polarization degrees.

TABLE 1

K Band Polarization around GL 490 and R Monocerotis

Object	Offset	P_K	P.A.
GL 490......	(0″, −30″)	6.9% ± 1.0%	111°
	(−20, −20)	19.0 ± 2.4	142
	(−30, 0)	13.9 ± 2.4	165
R Mon	(20, 20)	49.2 ± 0.8	131
	(0, 30)	17.5 ± 1.5	90
	(−20, 20)	12.6 ± 0.5	50

about 0.1 pc from the central source compared with the brightness temperature of about 240 K. Free-free emission is unplausible because of the weak radio continuum (1.9 mJy at 2 cm in the immediate vicinity of GL 490; Campbell, Persson, and McGregor 1986) and weak Bγ emission ($< 1.9 \times 10^{-20}$ W cm^{-2} μm^{-1} for R Mon; Thompson and Tokunaga 1979). However, nonequilibrium thermal emission from small dust grains found for visual reflection nebulae by Sellgren (1984) cannot be excluded definitely from rough estimates like those above. We therefore made polarimetric measurements for diffuse emissions. Table 1 presents the polarization in the diffuse emissions around GL 490 and R Mon. The large degrees (7% ~ 50%) and the directions (perpendicular to the lines connecting the central source itself and the positions observed, although those for GL 490 may be slightly affected by polarization due to dichroic absorption through the foreground cloud) of them indicate that the diffuse emissions are produced by reflection of light from the central sources. Thus we conclude that the diffuse emissions around GL 490 and R Mon are infrared reflection nebulae.

The most conspicuous feature of the infrared reflection nebulae is a ridge structure enclosing a dimmer region. This feature is not seen on the *i*(6600 Å), *r*(8000 Å), and *z*(9000 Å) band images of GL 490 (Campbell, Persson, and McGregor 1986) nor on *B*(4600 Å), *V*(5400 Å), and *R*(7600 Å) band images of R Mon (Aspin, McLean, and Coyne 1985). The presence of a new feature in the *K* band is attributable to the fact that the sources are optically thin in the *K* band but thick at shorter wavelengths.

In the optically thin case, the surface brightness straightforwardly reflects the distribution of the scatterer, dust, because the reflected light is proportional to the incident light times the column density of dust grains. Furthermore, it is of interest to note that the curved ridge around R Mon just encloses the blueshifted wing component in a high-resolution (18″) CO map Kaifu *et al.* (1989) (see Fig. 4). Maps of GL 490 bipolar outflow now available do not have enough spatial resolution to be compared with our *K* band map. Low-velocity red-shifted components of HCO$^+$ and HCN emissions show a pair of shell (H-shaped) structures (Kawabe *et al.* 1987). Our *K* band map traces the root of the HCN shell (Fig. 3), although the spatial coincidence with the HCO$^+$ emission is not so good as with HCN emission. Therefore, we suggest that the dense shell actually encloses the bipolar molecular flow.

This shell structure mimics that discovered for the wing component of CO emission in the L1551 bipolar flow (Snell

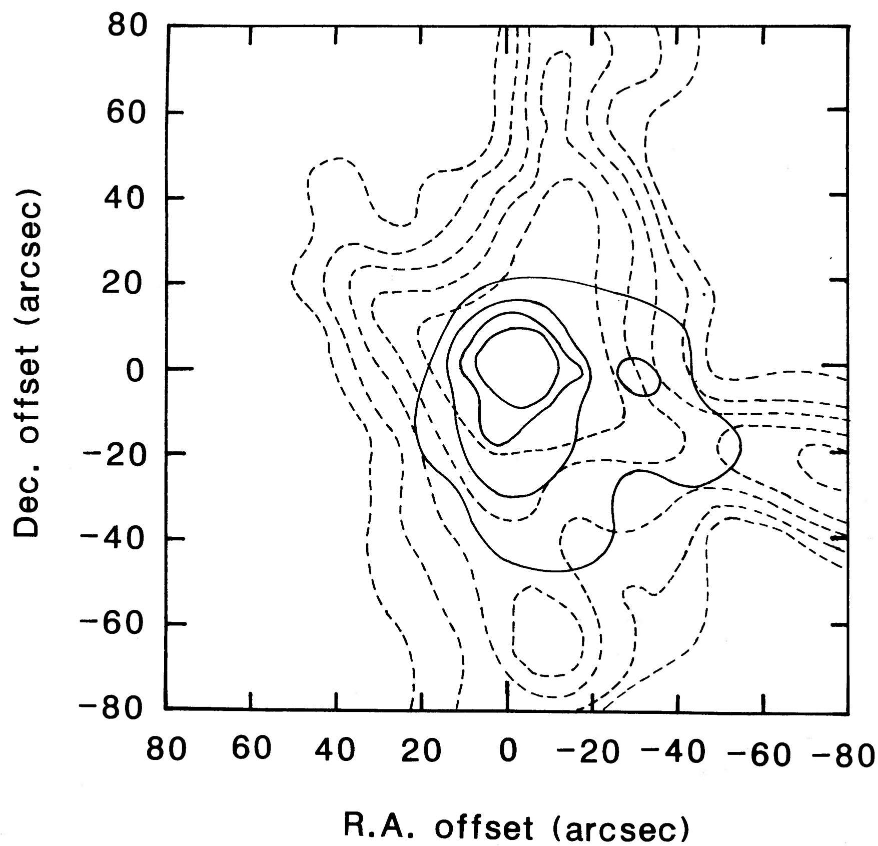

Fig. 3.—A *K* band map of GL 490 (*solid lines*) superposed on the low-velocity redshifted HCN emission (*dashed lines*; Kawabe *et al.* 1988). The map center is the same as in Fig. 1. Contours are dimmed for the purpose of simplicity.

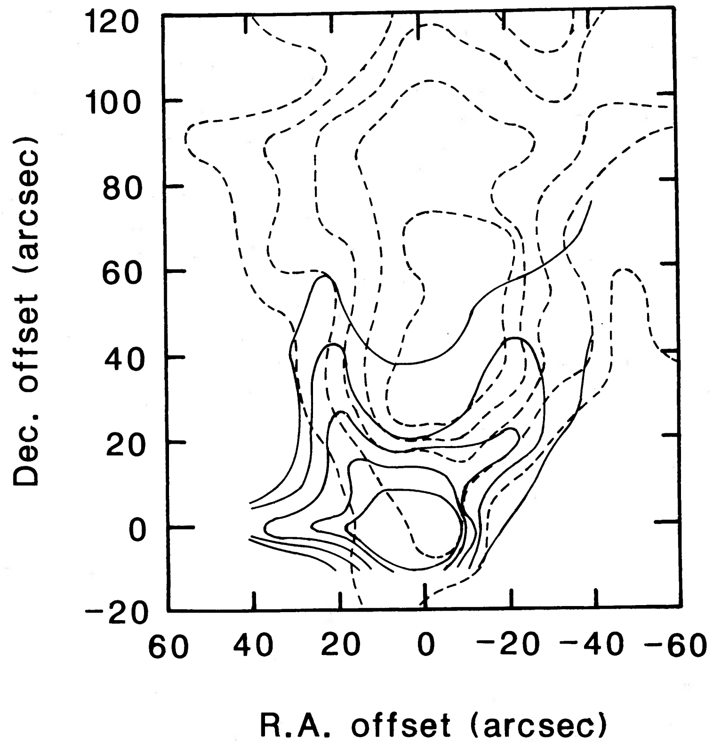

FIG. 4.—A K band map of R Mon (*solid lines*) superposed on the blueshifted lobe of the CO bipolar flow (*dashed lines*; Kaifu *et al.* 1989). The map center is the same as in Fig. 2. Contours are dimmed for the purpose of simplicity. Note that the K band emission clearly encloses the blueshifted flow.

and Schloerb 1985; Uchida *et al.* 1987) and the HCO^+ and HCN emissions in the GL 490 bipolar flow. The molecular line maps, however, do not necessarily represent the distribution of the whole material because the structure is seen only at a particular velocity. On the other hand, scattered light, in the optically thin case, directly reveals the distribution of dust as discussed above.

Independent observations of R Mon by Warren-Smith, Draper, and Scarrott (1986) show similar structure in the I band (9000 Å), although not in the R band (7000 Å). This suggests that the infrared reflection nebula around R Mon is becoming optically thin in the I band. Beckwith *et al.* (1986) also found a ridge structure extending for about 30″ to the northeast from R Mon itself in an aperture synthesis map of CO emission (11″ × 6″ beam). Comparing these similar structures one finds a spatial shift, in that the CO ridge is innermost and the K band one is outermost. We interpret this shift as an effect of optical thickness; the optical depth in the I band is marginally thin and the reflection occurs mainly at the surface of the shell, while the CO ridge would represent a warm still inner surface heated by UV photons, which have the shortest mean free path.

In addition to the ridge structure, the map of R Mon shows an extension to the east, perpendicular to that of the reflection nebula (Fig. 2). This extension coincides spatially with the eastern part of a CO disk revealed by Cantó *et al.* (1981) and Kaifu *et al.* (1989). Therefore, we regard this feature as due to light scattered by the dust in the disk. The absence of a western counterpart of the disk is attributable to still higher dust density, by which the near-infrared photons are extinguished. This interpretation is consistent with the observation of stronger ^{13}CO emission in the west side than in the east side (Kaifu *et al.* 1989).

b) The Large Dust Grains around R Monocerotis

We next discuss dust properties in the infrared reflection nebula around R Mon, which is possible because scattering around R Mon is considered to be completely thin in the K band; that around GL 490 may be only marginally optically thin.

A column density and a density of the shell are calculated from the optical depth in the K band. The optical thickness along the line of sight is obtained, for the optically thin case, from the following relation

$$\tau_{\rm scatt} = 4\pi \times r^2 \times S.B./F_* \,, \tag{1}$$

where $\tau_{\rm scatt}$ is the optical thickness of scattering, r is the angular distance from the central source to the nebular component being discussed, $S.B.$ is the surface brightness (flux density per square arcsec), and F_* is the intrinsic flux density of the central source. Applying this to the nebular component at 30″ north of R Mon, we obtain an optical thickness of 0.2 taking a visual extinction of 4 mag toward R Mon itself (Low *et al.* 1970) into consideration. The uncertainty of the correction of extinction may affect the result if it is large. However, visual magnitude of 11.87 for R Mon itself (Low *et al.* 1970) compared with intrinsic one of 6.7 for B2 V star at the distance of 700 pc (Low *et al.* 1970) indicates that the visual extinction toward the hot dust region around R Mon is less than 5.2 mag, which corresponds to 0.6 mag in the K band. Therefore, the uncertainty of the correction due to extinction does not affect the result so much.

The optical thickness of 0.2 corresponds to a column density of 1×10^{22} cm^{-2} according to the next relation:

$$N(H_2)_{\rm scatt} = 5 \times 10^{22} \times \tau_{\rm scatt}\ ({\rm cm}^{-2}) \,, \tag{2}$$

where $N(H_2)_{\rm scatt}$ is the column density of molecular hydrogen (Draine and Lee 1984). This deduced column density is larger than that determined from ^{12}CO and ^{13}CO observations by Cantó *et al.* (1981). Their observations showed a ^{13}CO column density of 3×10^{15} cm^{-2}, which corresponds to a hydrogen column density [$N(H_2)_{CO}$] of 1.5×10^{21} cm^{-2} (Dickman 1978). The column density derived from infrared scattering applies only to that material which is illuminated by R Mon, whereas that from molecular line observations is an integral along the line of sight. In addition, the 66″ beam of CO observations was centered on R Mon itself to which the column density is considered to be larger than the region under discussion. If the optically thin assumption breaks down in the infrared, the derived column density becomes only a lower limit. Thus $N(H_2)_{scatt}$ must always be smaller than $N(H_2)_{CO}$. However, $N(H_2)_{scatt}$ is larger than $N(H_2)_{CO}$ by nearly an order of magnitude.

This discrepancy is unlikely to be attributable to a systematic difference between the two methods, which compare dust properties and molecular line excitation, because the relation between visual extinction and ^{13}CO column density is observationally established within an error of 50%, much smaller than an order of magnitude, for $A_V = 1.5 \sim 10$ (Dickman 1978; Bachiller and Cernicharo 1986), while the visual extinction calculated from the scattering optical depth τ_{scatt} is obtained from a relation which explains extinction law between 1000 Å and 10 μm in interstellar space (Draine and Lee 1984). Therefore, our discussion should be applicable, at least, to interstellar dust grains.

We suggest that the apparent discrepancy in our analysis arises because the model for interstellar dust grains is inappropriate for the region around R Mon. This discrepancy can be resolved if the dust grains in this region are large; the scattering cross section is larger for larger grains. The large grain hypothesis has already been advanced for star-forming regions and dark clouds on other grounds. Rouan and Leger (1984) derived a mean grain radius of about 0.5 μm from a model calculation for the dust condensation, IRC 4, in Orion. Several authors (e.g., Carrasco, Strom, and Strom 1973; Vrba, Coyne, and Tapia 1981) found that the peak wavelength, λ_{max} of polarization of field stars through dark clouds is larger than that of interstellar space.

The grains can grow larger by coagulation, accretion, or mantle growth. Accretion and mantle growth decrease the gas-to-dust ratio, whereas coagulation does not change the ratio; the dust size increases, but the numbers of grains decrease. However, coagulation increases scattering cross section because that for an individual dust grain is proportional to, at least, the fourth power of its radius. Accretion of less depleted atoms, such as C, N, and O, can explain our discrepancy in a sense that the largest grains, 1.8 times of interstellar ones, calculated from residual condensable elements in the gas (Greenberg 1978) have scattering cross section of about 10 times larger. Mantle growth on the grain surface also increases its size. However, R Mon itself does not show absorption feature of ice at 3.1 μm (Cohen 1975), which is thought to be one of the abundant constituents of the mantle. Solid CO may be present in the mantle of dust grain as well as in other regions (e.g., Lacy *et al.* 1984), but the mass of solid CO found for Taurus dark cloud (Whittet, Longmore, and McFadzen 1985) is much less than that of the dust itself as well as an ice mantle in ρ Oph (Harris, Woolf, and Rieke 1978). Therefore, it is implausible for solid CO to increase the grain size largely, although CO depletion would diminish the discrepancy in our analysis in the way that it changes the relation between the CO and the H_2 column densities.

Thus we have added a new support on the large dust grains in the star forming regions. Future multiband observations are desired in order to confirm our suggestion and to obtain more precise information on dust grains.

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