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DISCOVERY OF A REFLECTION DUST ENVELOPE AROUND IRC +10216

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ABSTRACT

Infrared polarimetric and photometric mapping observations at K(2.2 μm) and H(1.65 μm) have revealed an extended dust envelope around the late-type star IRC +10216. The infrared envelope is nearly circularly symmetric with radial extent greater than 1′ ($\sim$0.09 pc), comparable to the size of the molecular gas envelope. The polarization vectors of the near-infrared continuum radiation from the envelope show a clear centrosymmetric pattern, indicating that the infrared nebulosity is due to scattering by dust grains in the envelope. The radial distribution of dust grains inferred from the polarized intensity most likely obeys an inverse-square law, which suggests a steady mass loss between $r \approx 15''$ and $60''$.

Subject headings: infrared: sources — polarization — stars: late-type — stars: mass loss

I. INTRODUCTION

Although late-type stars are supposed to contribute significantly to the supply of interstellar dust grains, our knowledge about the amount and the properties of dust grains in their circumstellar envelopes is very limited. This is also the case for the well-studied particular object IRC +10216, a late-type carbon star (Cohen 1979) of extreme brightness at near-infrared and mid-infrared wavelengths (Becklin *et al.* 1969; Witteborn *et al.* 1980). A large amount of mass loss from the star makes an envelope of gas and dust. The *gas* envelope extending out to a few arcminutes from the star has been revealed by molecular line observations at millimeter wavelengths (Morris *et al.* 1975; Bieging, Chapman, and Welch 1984; Kuiper *et al.* 1976; Wilson, Schwartz, and Epstein 1973; Wootten *et al.* 1982; Wannier *et al.* 1979). On the other hand, the size of the *dust* envelope observed at visible, near-infrared, and mid-infrared wavelengths has been reported to be much smaller (less than 2″) based on the observations of lunar occultations (Toombs *et al.* 1972), measurements of infrared speckles (Dyck *et al.* 1984; Mariotti *et al.* 1983), and other interferometric observations (McCarthy, Low, and Howell 1977; Sutton *et al.* 1979). Attempts to measure the size of the dust envelope in the far-infrared have yielded controversial results. Fazio *et al.* (1980) measured the source size of $\sim$0′.9 at 40–250 μm, while Lester, Harvey, and Joy (1986) detected no extended emission at the 1% level of the central source at 50 and 100 μm; their results appear inconsistent with each other. The nondetection of the extended dust envelope, if confirmed, would imply that the dust-to-gas ratio or the bulk emissivity of the grains are fairly low (Lester, Harvey, and Joy 1986).

Polarimetry of scattered light around late-type stars gives useful information on the distribution and optical properties of scatterers, i.e., dust grains in circumstellar envelopes. Combined with the observations of the gas component in millimeter molecular lines, these measurements would enable us to estimate the dust-to-gas ratio in the envelope. In this *Letter*, we report the detection of an extended ($\gtrsim 1'$) reflected light around IRC +10216, demonstrating the potential of the polarimetric observations mentioned above. The data reveal for the first time the distribution of dust grains in the outer envelope of the star.

II. OBSERVATIONS AND RESULTS

All the observations presented here were made on the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. In 1985 December, we discovered highly polarized (up to 30%) diffuse light around IRC +10216 in the K band (2.2 μm) at several positions 10″–50″ away from the star. The extensive polarization map at K presented here was made by employing the Kyoto polarimeter and the photometer UKT6 in 1987 January and February. The position angle was calibrated by observing a highly polarized star (GL 2591; P.A. = 171°, Lonsdale *et al.* 1980). The photometric map at K was made with UKT9 in 1985 December. The intensity standard was HD 106965 (7.3 mag, Elias *et al.* 1982). A beam size of 20″ and 12″ was used for photometric and polarimetric observations, respectively. The chopping frequency, direction, and separation of each observation were 3.5 Hz, E–W, and 2′; of the positions east and west of the peak only, we employed N–S chopping. The K band polarization map superposed on the K band photometric map is shown in Figure 1.

The polarization map at K in Figure 1 shows a clear centrosymmetric pattern of polarization vectors. Ninety-two percent (27 of 29) of the normals of the polarization vectors in Figure 1 converge on the center within an error of 10°. This pattern of the polarization vectors and the large degrees of polarization up to 30% indicate that the observed nebulosity is scattered light (Heckert and Zeilik 1983) which is similar to the cases of infrared reflection nebulae around young stars (e.g., Werner,

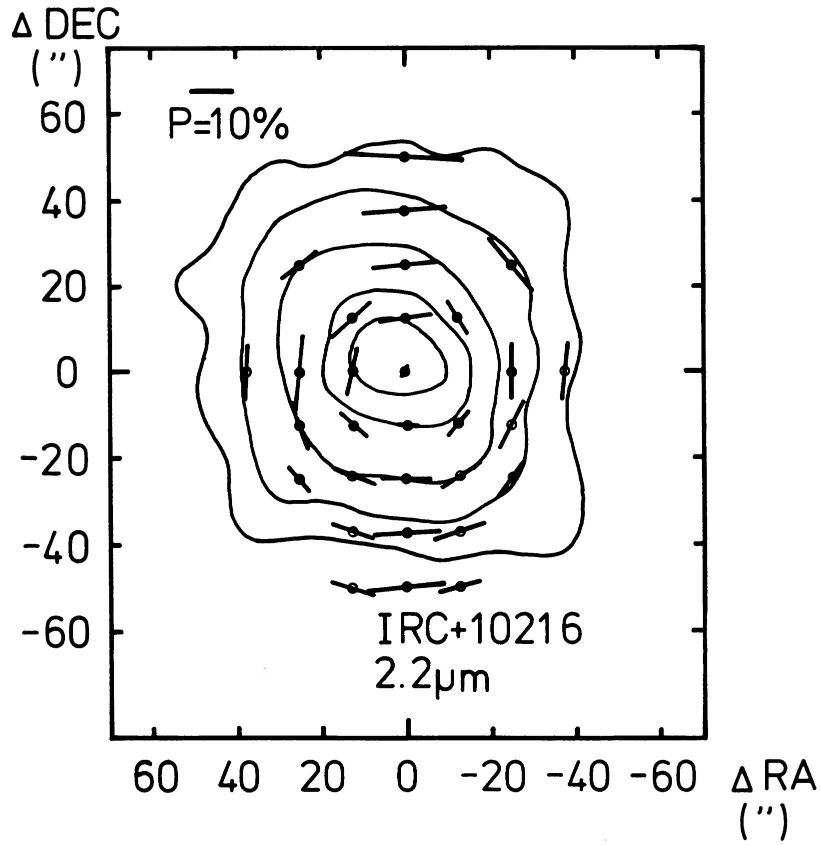

FIG. 1.—Surface brightness and polarization map of IRC +10216 in the *K* band, with the beam size of 20″ and 12″, respectively. Contour levels are 1.5, 3.1, 9.4, 94, and 940 × 10^{-21} W cm^{-2} μm^{-1} $arcsec^{-2}$. Filled and open circles in the middle of the polarization vectors indicate positions of polarimetry made in 1987 January and February, respectively.

Dinerstein, and Capps 1983; Heckert and Zeilik 1984; Castelaz *et al.* 1985).

Since Figure 1 shows a roughly circular symmetry, it may be justified to study the radial distribution of the light from one-dimensional scans through the star. We made *K* and *H* (1.65 μm) polarization scans toward the south from IRC +10216 and a corresponding null test on bright stars to check the contamination by stray light in the telescope and instruments; these measurements were made with the Kyoto polarimeter and UKT9 using a 12″ beam in 1987 February. The results of the polarization scans are tabulated in Table 1, together with those of the null tests on unpolarized stars.

The measurements of surface brightness and degrees of polarization in Figure 1 were contaminated by instrumental stray light because of the limited dynamic range of the optical system and the extreme brightness of the star. In fact, we detected an appreciable intensity ($\sim 10^{-4.9}$ of the intensity on the star) even at 1′ from a *normal* star, and the effect of the spider of the telescope might make the apparent shape of the envelope rather rectangular as can be noticed in Figure 1. However, the polarized intensity (degree of polarization times the intensity) is a good measure of the reflection envelope, free from contamination by stray light in the telescope and instruments, as we have demonstrated by measurements of polarization around unpolarized stars: α Leo in the same pattern as we scanned through IRC +10216, and α CMi in a different pattern. Although the signal-to-noise ratio is not good enough at the positions greater than 30″ in the case of α Leo, Table 1 shows that the polarized intensity from the instrumental stray light contributes no more than 15% of the *polarized* intensity observed around IRC +10216 except at $r = 15''$.

The radius of the roughly circular symmetric envelope inferred from Table 1 and Figure 1 is about 1′ (0.09 pc for the assumed distance to IRC +10216 of 300 pc; Herbig and Zappala 1970), which is comparable to that of the gas envelope observed in molecular lines (HCN, 20″—Bieging, Chapman, and Welch 1984; CO, 2′—Wilson, Schwartz, and Epstein 1973; Wannier *et al.* 1979; CN, 70″—Wootten *et al.* 1982).

We also measured the polarization around another late-type star CIT6 at three positions (Table 1). There is weak evidence of an extended envelope in that source because the position angles of the polarization "off-the-peak" are nearly at right angles with the line joining the center and observed positions.

III. DISCUSSION

The radial distribution of polarized intensity can be used to derive the dust density gradient $\rho = \rho(r)$.

In Figure 2 is plotted the polarized intensity at *K*, *PI*, normalized by the central intensity, I_0, versus the projected radial distance from the center, *r*. Although two sets of data (*filled and open circles*) were taken with different instruments on different days, all the data can be well fitted by the relationship:

$$\log (PI/I_0) = (-3.1 \pm 0.3) \log r + (-0.2 \pm 0.4) . \quad (1)$$

To derive the density law we have employed a simple model similar to those for the shell around α Ori (McMillan and Tapia 1978; Jura and Jacoby 1976). The model assumes that the envelope is optically thin, spherically symmetric, and com-

TABLE 1

RESULTS OF POLARIZATION SCANS AND NULL TESTS

	POLARIZATION SCANS						NULL TESTS									
	IRC +10216/K Band			IRC +10216/H Band			Alpha Leo/K Band			Alpha CMi/K Band				CIT 6		
Position[a] (1)	P(K)[b] (2)	P.A.(K)[c] (3)	log (PI/I_0)[d] (4)	P(H)[b] (5)	P.A.(H)[c] (6)	log (PI/I_0)[d] (7)	$P(K)$[b] (8)	P.A.(K)[c] (9)	log (PI/I_0)[d] (10)	Position[a] (11)	P(K)[b] (12)	P.A.(K)[c] (13)	log (PI/I_0)[d] (14)	Position[a] (15)	$P(K)$[b] (16)	P.A.(K)[c] (17)
0	2.02% ± 0.19%	154°	...	2.38% ± 0.11%	150°	...	0.07% ± 0.08%	7°	...	20″S	0.49% ± 1.49%	146°	< −4.91	0	0.83% ± 0.16%	73°
15″S	7.04 ± 1.03	83	−3.93	9.18 ± 1.00	92	−3.58	2.92 ± 1.95	37	< −3.75	40″S	0.79 ± 0.48	5	< −6.26	25″S	3.01 ± 0.79	80
25″S	9.48 ± 0.84	88	−4.62	14.13 ± 0.82	91	−4.21	1.23 ± 0.98	98	< −5.15	30″S30″E	0.43 ± 0.35	172	< −6.08	15″S15″W	1.77 ± 0.80	116
35″S	11.44 ± 0.69	88	−5.03	14.79 ± 1.87	99	−4.74	0.22 ± 1.14	76	< −5.93	50″S50″E	0.16 ± 0.41	54	< −6.64	...	...	...
45″S	10.29 ± 0.81	93	−5.36	10.80 ± 2.99	91	−5.19	2.56 ± 2.82	143	< −5.71	60″S	0.28 ± 0.58	142	< −6.91	...	...	...
55″S	9.08 ± 1.41	90	−5.72	...	...	...	4.83 ± 4.92	135	< −5.70	...	...	...	...	...	...	...
65″S	11.46 ± 1.94	85	−5.86	...	...	...	12.88 ± 9.18	121	< −5.61	...	...	...	...	...	...	...

[a] Relative position to the peak.
[b] Degree of polarization and its error.
[c] Position angle.
[d] Polarized intensity normalized by the peak intensity.

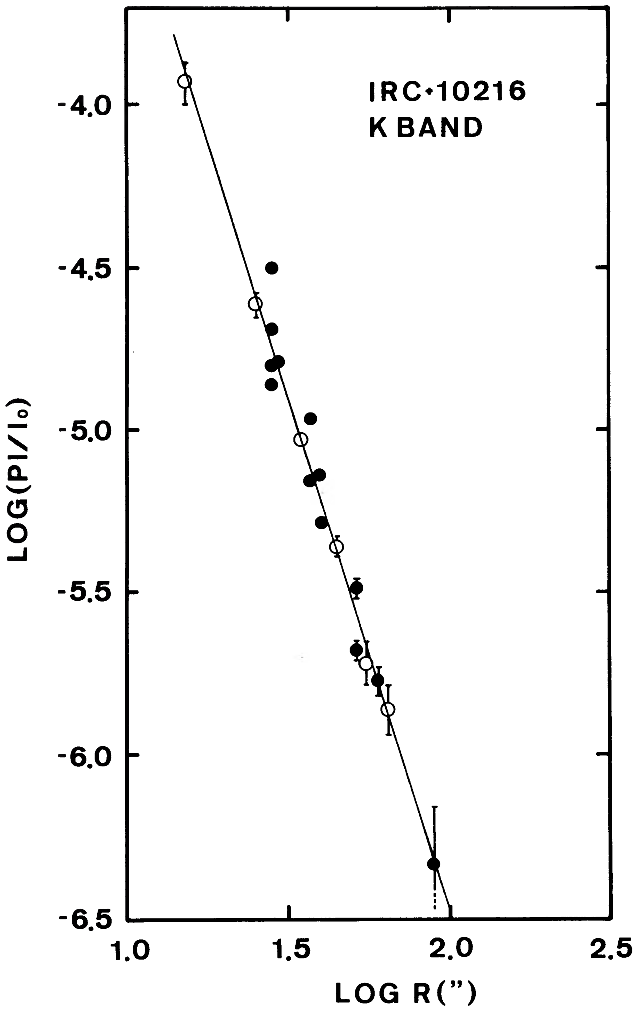

FIG. 2.—Logarithmic radial distribution of the polarized intensity of the envelope of IRC +10216 in the *K* band. Open circles were data taken with the photometer UKT 9 on 1987 February 16, while filled circles were data taken with UKT 6 on 1987 February 15. A least-squares-fitted line, $\log(PI/I_0) = -3.14 \log r - 0.19$, is shown by a thin line.

posed of isotropic scatterers with a density distribution proportional to r^{-c}. These assumptions seem plausible in this case if we note the spherically symmetric shape of the envelope and the large polarization up to 30%.

Then the normalized polarized intensity is

$$\log(PI/I_0) = -(c+1)\log r + \log \tau_{\rm scat} + \log(r_0/R) + 1.1 , \quad (2)$$

where $\tau_{\rm scat}$ is the optical depth for scattering, r_0 is the inner boundary of the nebulosity, and R is the distance from the Sun.

A least-squares fit to the data in Figure 2 at K gives the exponent $c = 2.1 \pm 0.3$, and for the data at H, $c = 2.4 \pm 0.3$. This suggests that the dust distribution around IRC +10216 is consistent with obeying an inverse-square law. This would imply a constant mass-loss rate between $r = 15''$ and $60''$, the limit for the data.

Although several molecular line observations suggest that the mass loss from IRC +10216 is not uniform, but is decreasing with time (e.g., Sahai 1987), our data suggest that the change of mass loss rate is less than 50% between $r = 15''$ and $60''$. Sahai (1987) in fact models the mass loss in the gas envelope with a two-component model; his best fit to the available CO data has $\dot{M} = 3.2 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ for $1'' < r < 6''$ and $\dot{M} = 4.8 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ in the extended envelope (i.e., $r > 6''$), suggesting a phase of reduced mass loss in the inner envelope. Our data are unable to address the mass-loss rate in the inner envelope.

We can estimate both the dust mass in the envelope and the mass-loss rate if we assume the size of the dust grains, a, to be 0.1 μm, typical in the interstellar medium.

If the density gradient is assumed to obey a r^{-2} law, the optical depth for scattering $\tau_{\rm scat}$ is determined to be 0.18 ± 0.05 from equations (1) and (2). For this calculation, we assumed that $r_0/R = 0''.2$, the radius of the central unresolved region at 2.2 μm (Toombs *et al.* 1972; Dyck *et al.* 1984). Using a scattering efficiency, $Q_{\rm scat}$, of 0.0123 for 0.1 μm graphite grains (Draine 1985) and a grain density of 2.26 g cm^{-3} (Draine and Lee 1984), we estimate that the dust mass in the envelope within 1′ in radius is $6.7 \times 10^{-4}[a(\mu{\rm m})/0.1]^{-3}\ M_\odot$, where was used the relation that $Q_{\rm scat}$ varies as a^4 for Rayleigh scattering.

The mass-loss rate, $\dot{M}_{\rm dust}$, is derived as

$$\dot{M}_{\rm dust} = 1.2 \times 10^{-7}[a(\mu{\rm m})/0.1]^{-3}(V_{\rm dust}/V_{\rm gas})^{-1}\ M_\odot\ {\rm yr}^{-1} ,$$

where we might tentatively assume that the outflow velocity of dust grains, $V_{\rm dust}$, is not very different from the mass-loss speed of the gas, $V_{\rm gas}$ (= 15 km s^{-1}). This can be compared with the gas mass-loss rate derived from molecular observations (Sahai 1987) to get an estimation of the dust-to-gas mass ratio;

$$\dot{M}_{\rm dust}/\dot{M}_{\rm gas} = 0.24[a(\mu{\rm m})/0.1]^{-3}(V_{\rm dust}/V_{\rm gas})^{-1}\% .$$

The estimated ratio is close to those in interstellar clouds (0.7%; Savage and Mathis 1979), if we take into account that the dust-to-gas ratio in stellar envelopes may strongly reflect the metalicity of the stellar atmospheres and the efficiency for the heavy elements to condense on grains and may differ by orders of magnitude from star to star. Measurements of the infrared reflection nebulosity around other late-type stars would give valuable information on the dust grains formed in the stellar envelopes and supplied to the interstellar matter.

Finally, we should point out that the near-infrared polarization at the position of the star of IRC +10216 has shown a considerable change in its position angle in the last 8 yr: our observation toward the peak is $P(2.2\ \mu{\rm m}) = 2.33\% \pm 0.11\%$ and P.A.(2.2 μm) = 158° ± 1°, while earlier measurements give $P(2.2\ \mu{\rm m}) = 1.6\% \pm 0.1\%$ and P.A.(2.2 μm) = 116° (Dyck, Forbes, and Shawl 1971) and P.A.(7000 Å) ≈ 118° (Cohen and Schmidt 1982, observations in 1979). This might suggest that the distribution of dust is slightly asymmetric about the star within the distance suggested by the time scale of the change, i.e., 8 yr × 15 km s^{-1} = 25 AU.

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