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EXTENDED NEAR INFRARED EMISSION FROM VISUAL REFLECTION NEBULAE

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ABSTRACT

Extended near infrared (2–5 μm) emission has been observed from three visual reflection nebulae, NGC 7023, 2023, and 2068. The emission from each nebula consists of a smooth continuum, which can be described by a greybody with a color temperature of 1000 K, and emission features at 3.3 and 3.4 μm. The continuum emission cannot be explained by free-free emission, reflected light, or field stars, or by thermal emission from grains, with commonly accepted ratios of infrared to ultraviolet emissivities, which are in equilibrium with the stellar radiation field. A possible explanation is thermal emission from grains with extremely low ratios of infrared to ultraviolet emissivities, or from grains with a temperature determined by mechanisms other than equilibrium radiative heating. Another possibility is continuum fluorescence.

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I. INTRODUCTION

This paper reports photometric and spectrophotometric observations of extended near infrared emission from three visual reflection nebulae, NGC 7023, 2023, and 2068. These observations reveal that the near infrared emission in all three nebulae consists of a smooth continuum which can be described by a color temperature of ~ 1000 K, and strong emission features at 3.3 and 3.4 μm. Emission processes hitherto thought to be important in infrared sources appear to be incapable of explaining these observations.

II. OBSERVATIONS

Observations were made of NGC 7023, 2023, and 2068 on 1982 October 8-13 using the Infrared Telescope Facility at Mauna Kea Observatory. A solid nitrogen cooled InSb detector was used with standard photometric filters at K (λ = 2.20 μm, $\Delta\lambda$ = 0.42 μm), L' (λ = 3.77 μm, $\Delta\lambda$ = 0.66 μm), and M (λ = 4.8 μm, $\Delta\lambda$ = 0.57 μm). A circular variable filter wheel with 1% resolution from 1.9 to 3.7 μm was also used.

The observations were made with a 12″ diameter diaphragm, and a spacing in right ascension between source and sky positions of 2-3′. Maps at 2.2 μm of the extended emission in the nebulae (Sellgren 1983) were consulted in order to ensure that the surface brightness of the sky positions was negligible.

The observations were calibrated using standard techniques, described in more detail by Sellgren (1983). The observations of NGC 7023 have been corrected for the contribution of instrumental scattered light from the illuminating star of the visual reflection nebula. This correction, about 10% at most, was determined by observations of isolated bright stars.

III. RESULTS

Spectrophotometry of the extended emission in NGC 7023 and NGC 2023 from 1.9 to 3.7 μm is shown in Figure 1. The near infrared emission consists of a smooth, relatively flat continuum and a bright emission feature at 3.3 μm, with a broad emission wing centered at 3.4 μm. These features at 3.3 and 3.4 μm have been observed in other infrared sources (Aitken 1981). The broadband photometry at 2.2, 3.8 and 4.8 μm is also shown in Figure 1. The 3.8 μm broadband filter extends from 3.44 to 4.10 μm, so that it should exclude the strong 3.3 μm feature and most of the weaker 3.4 μm feature. The spectra of both sources look very similar, both in the continuum shape and in the strength of the 3.3 μm feature relative to the continuum.

Table 1 gives the 2.2, 3.8, and 4.8 μm surface brightnesses of all positions observed in NGC 7023, 2023, and 2068. The shape of the continuum emission from NGC 7023 and 2023 can be characterized by the temperature of a greybody passing through the broadband points. The 2.2 to 3.8 μm color temperatures can be seen in Table 1 to be similar at all positions in these nebulae, ranging from 900 to 1100 K. The 2.2 to 4.8 μm color temperature ranges from 900 to 1300 K.

The strength of the 3.3 μm emission feature, relative to the continuum, also varies little among the various nebular positions. Table 1 gives the observed surface brightness at the peak of the 3.3 μm feature, measured with the 1% circular variable filter wheel. It also gives the ratio of the 3.3 μm feature, corrected for the continuum at 3.3 μm estimated from the 2.2 and 3.8 μm broadband points, to the 3.3 μm continuum. The feature-to-continuum ratio in NGC 7023, 2023, and 2068 is nearly constant, with values between 3 and 8, and an average value of 6. For comparison, the sources discussed by Dwek *et al.* (1980) have 3.3 μm feature-to-continuum ratios of 0.4 to 4, while the observations of the Orion nebula by Sellgren (1981) show that the 3.3 μm feature-to-continuum ratio in that source varies from < 0.15 to 7 across the nebula. Thus the 3.3 μm feature-to-continuum ratios observed in the three reflection nebulae are among the highest found, and furthermore are considerably more constant than is observed from source to source in other objects, or between different positions in spatial mapping of the Orion nebula.

IV. DISCUSSION

Our observations pose two separate questions. The first is the origin of the unidentified emission features, which is a long-standing mystery. The second is the source of the extended continuum emission. As is discussed below, the emission mechanisms believed to be important in other infrared sources are inadequate to explain the continuum emission, particularly the high and uniform color temperature over an extended region. The association in these visual reflection nebulae of the strong 3.3 μm feature with the anomalous continuum emission, as shown by the constant 3.3 μm feature-to-continuum ratio, suggests that the two phenomena may have similar explanations or even a common physical basis.

a. The 3.3 μm emission feature

The emission feature at 3.3 μm and its wing at 3.4 μm, observed in the three reflection nebulae, are two of six unidentified infrared emission features between 3.3 and 11.3 μm, usually seen together, for which neither the material nor the emission mechanism is known. The breadth of the features (Tokunaga and Young 1980; Grasdalen and Joyce 1976; Bregman and Rank 1975) indicate that the emitting material is in the solid phase. Current models for the emission mechanism, fluorescence excited by ultraviolet (UV) radiation (Allamandola, Greenberg, and Norman 1979) and thermal emission from small grains heated by UV radiation (Dwek *et al.* 1980), fail to explain the observed 3.3 μm emission in the reflection nebulae. The fluorescence model requires too high a UV fluorescence efficiency (Dwek *et al.* 1980), while the thermal emission model is unable to account for the high brightness temperature of the 3.3 μm emission, 190K.

b. The extended near infrared continuum emission

Many possible emission mechanisms have been investigated in searching for the source of the observed extended near infrared continuum emission; detailed arguments will be given in a later paper (Sellgren 1983). The following emission mechanisms appear to be unable to account for the continuum emission:

1) Free-free emission. Measurements of 6 cm emission in NGC 2023 and 2068 and upper limits on 6 cm emission from NGC 7023 (Sellgren *et al.* 1983) predict near infrared surface brightnesses due to free-free emission accounting for less than 1% of the observed near infrared emission.

2) Reflected light. The observed surface brightness of NGC 2023 exceeds by a factor of 3 at 2.2 μm, and a factor of 20 at 3.8 μm, the maximum surface brightness possible for reflected light from any of the known stellar sources associated with the region, including the visual illuminating star. Similarly NGC 7023 and 2068 are brighter by factors of 5-6 at 3.8 μm than the maximum possible surface brightness of reflected light. The true contribution of reflected light to the observed infrared surface brightness is probably significantly less than the maximum possible, since the actual nebular geometries and grain properties will likely differ from those which produce the maximum amount of reflected light.

3) Faint stars. An argument against the observed emission being due to faint members of the stellar clusters associated with the reflection nebulae is that the emission appears uniformly extended, in diaphragms with diameters between 6" and 60". Furthermore, Sellgren (1983) has shown, using the surface density of stars and luminosity functions observed in these regions, that the expected 2.2 μm surface brightness from faint stars is < 10% of the observed 2.2 μm emission.

4) Thermal emission from "normal" dust. The observed constancy of the continuum color temperature with distance from the central star is a problem for explaining the observations by thermal dust emission. A more severe problem, however, is the high value of the inferred dust temperature. The brightness temperature of the 2.2 μm emission is ~ 240 K in the three reflection nebulae, implying a minimum dust temperature of 240 K if the emission is due to thermal dust emission. In fact the dust presumably would have a temperature close to the observed color temperature of the emission, 1000 K, much higher than would be expected either from calculations or by comparison with observations of dust in other regions.

Near infrared emission is observed at a distance of 1' from the early B stars, with luminosities $L_* \sim 4-12 \times 10^3 L_\odot$, which illuminate the visual reflection nebulae. This 1' distance corresponds to $r \cong 0.15$ pc at the distances of the nebulae (Viotti 1969; Lee 1968). If the grains are in equilibrium with the stellar radiation field then the dust temperature T_d is given by $T_d = (Q_{UV} L_*)^{\frac{1}{4}}(16 \pi \sigma r^2 Q_{IR})^{-\frac{1}{4}}$, where Q_{UV} and Q_{IR} are the Planck averaged ultraviolet and infrared emissivities, and σ is the Stefan-Boltzmann constant. With $L_* = 10^4 L_\odot$ and $r = 0.15$ pc, $T_d = 17 (Q_{UV}/Q_{IR})^{\frac{1}{4}}$ K. The values of Q_{IR}/Q_{UV} predicted from calculations based on laboratory measurements of candidate grain materials (Draine 1981; Jones *et al.* 1977; Jones and Merrill 1976; Leung 1975; Aannestad 1975) fall between those corresponding to infrared emissivities proportional to λ^{-1} and λ^{-2}. These emissivities in turn imply $T_d = 70 - 150$ K.

In the Orion ridge (Becklin *et al.* 1976) grain temperatures of 60 - 300 K are seen, which, scaled to the lower fluxes of heating radiation appropriate to the visual reflection nebulae, would correspond to $T_d = 40 - 200$ K. Thus grain parameters derived either from calculations or from observations in other regions predict grain temperatures far below the observed color temperature of 1000 K, and well below even the 2.2 μm brightness temperature of 240 K observed in NGC 7023, 2023, and 2068. Both the far infrared observations (Whitcomb *et al.* 1981; Emerson, Furniss, and Jennings 1975; Harvey, Thronson, and Gatley 1980; Sargent 1982) and the radio observations (Sellgren *et al.* 1983) indicate that the visual illuminating stars are the most luminous stars in the reflection nebulae, so there do not appear to be any other sources of heating which might produce higher grain temperatures in these nebulae.

c. Speculations

The problem with explaining the near infrared emission lies in the shape of the energy distribution rather than its integrated luminosity, which is $\sim 10^{-2}$ of the total luminosity of the illuminating stars of the visual reflection nebulae The small luminosity of the unexplained continuum emission, and the fact that this emission was found in all three reflection nebulae observed, argue that the emission observed here may be a widespread phenomenon whose small contribution to the total luminosity of more complex regions may have been masked by other near infrared continuum emission mechanisms (e.g., free-free emission) with larger shares of the total luminosity.

While several mechanisms discussed above have failed to explain the observed emission, other possibilities exist which will be explored in more detail in a later paper (Sellgren 1983). One possibility is thermal emission from grains with a ratio of the average infrared emissivity to the average UV emissivity ~ 10^4 - 10^7 times lower than the ratio inferred from calculations or observations of other sources, in order to account for the extremely high color temperatures observed. In this case a mechanism to hold the grain temperature constant with distance from the star, such as a sublimation process, would also be needed. Another possibility for producing the observed continuum by thermal emission is very small grains, which momentarily reach a high temperature following the absorption of individual UV photons or after collisions (Harwit 1975; Purcell 1976). The peak temperature of such a thermally fluctuating grain would be to first order independent of position, thus explaining the lack of a radial temperature gradient in these sources. A third possible explanation is that fluorescence in grains produces not only emission features such as the 3.3 and 3.4 μm features, as suggested by Allamandola, Greenberg, and Norman (1979), but also a smooth continuum extending at least from 2 to 5 μm. Whatever the final explanation proves to be, it is clear that infrared observations of these nebulae have identified a phenomenon in the interstellar medium whose existence has not been previously suspected, and whose explanation may lead us to a better understanding of interstellar grains.

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Table 1

Position[a]	$S_{2.2}$[b]	$S_{3.8}$[b]	$S_{4.8}$[b]	$T_c\left[\frac{2.2}{3.8}\right]$[c]	$T_c\left[\frac{2.2}{4.8}\right]$[c]	$S_{3.3}$[b]	Feature[d] / Cont
				NGC 7023			
30″ W 20″ N	7.0	20	12 ±3	1020	1300 ±100	100	6.0
30″ N	5.5	18	24 ±6	980	940 ±70	74	5.0
60″ N	2.1	5.7 ±0.6		1060 ±50		36 ±3	7.6 ±0.8
60″ S	1.4	5.5 ±0.8		910 ±50		29 ±2	7.0 ±0.8
120″ N	0.31 ±0.04	<3.2		>690		<12	<15
				NGC 2023			
60″ S	4.6	15 ±1	9.8 ±3.5	990 ±30	1200 ±200	66	7.0 ±0.4
60″ N	2.0	5.1 ±0.5		1090 ±40		17 ±1	3.4 ±0.3
40″ W 40″ S	3.7	13 ±1		950 ±30			
				NGC 2068			
60″ E 40″ S	0.93	3.9 ±0.7		900 ±60		18 ±2	6.3 ±1.1

(a) Offset from illuminating star of visual reflection nebula, which is HD 200775, HD 37903, and HD 38563-N for NGC 7023, 2023, and 2068 respectively.

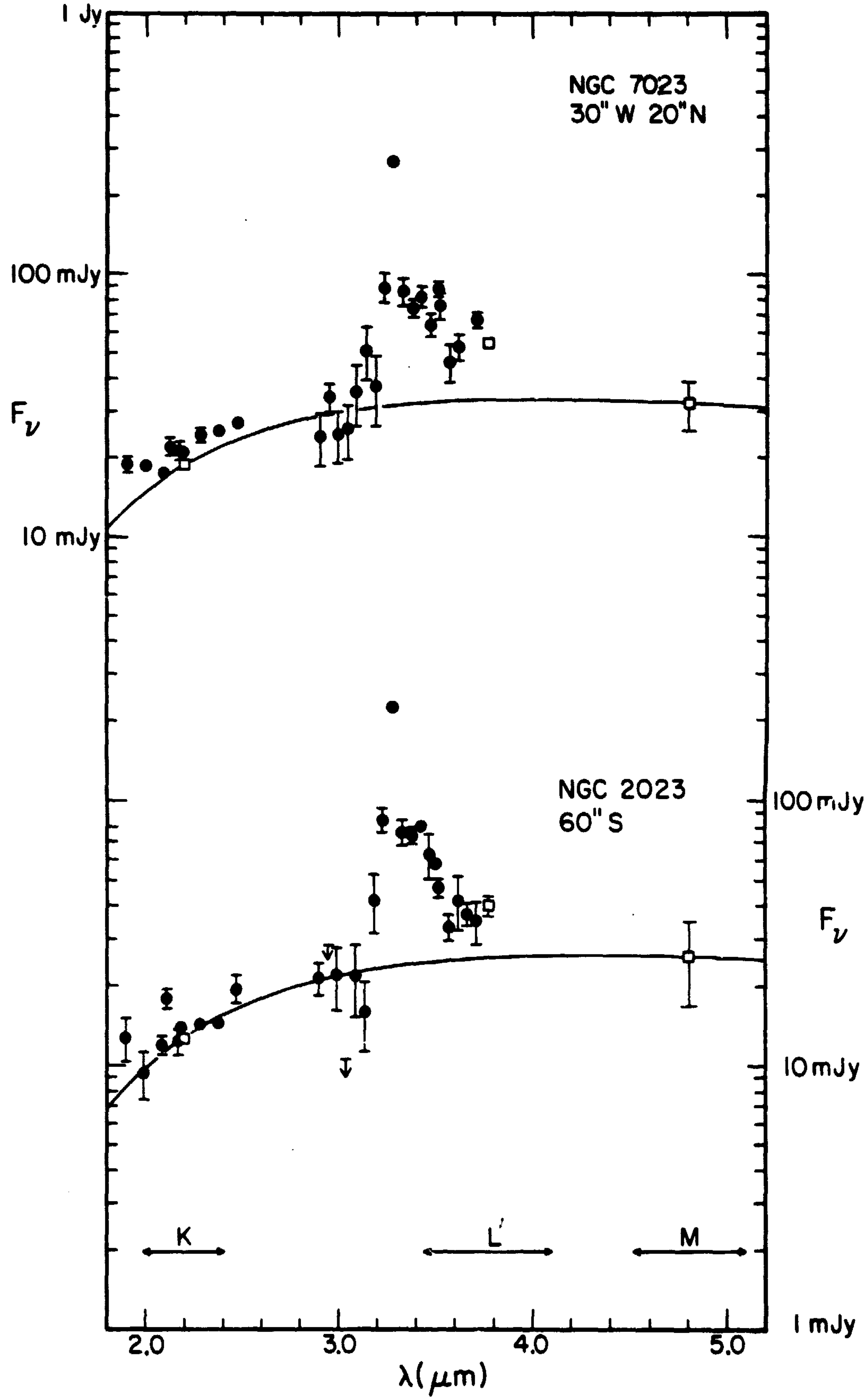
(*b*) Surface brightness measured with broad band filters at 2.2, 3.8, and 4.8 μm, and with 1% resolution at the peak of the 3.3 μm feature, uncorrected for continuum. Units are 10^{-20} W m^{-2} Hz^{-1} $ster^{-1}$. Uncertainties are $\pm 1\ \sigma$ and are given only when larger than 5%. All limits are 3-σ limits, except at NGC 2023 60" S, where the 4.8 μm observation given is a 2.8 σ measurement.

(*c*) Color temperatures (K) determined from ratios of surface brightnesses at 2.2 and 3.8 μm, and from ratios at 2.2 and 4.8 μm.

(*d*) Surface brightness in 3.3 μm feature, corrected for continuum, divided by 3.3 μm continuum surface brightness estimated from observed surface brightness at 2.2 and 3.8 μm. For NGC 7023 120" N, the 3.8 μm surface brightness was estimated from an average ratio of 2.2 to 3.8 μm surface brightnesses and the measured 2.2 μm surface brightness.

Figure Caption

Figure 1. Spectrophotometry (filled circles) with 1% resolution, from 1.9 to 3.7 μm, is shown of (*top*) NGC 7023 and (*bottom*) NGC 2023. Photometry (open squares) at 2.2, 3.8, and 4.8 μm is also shown. Error bars indicate $\pm 1\ \sigma$ statistical uncertainties when larger than 5 %. The units are mJy within a 12" diameter diaphragm; the left hand scale refers to NGC 7023 (*top*) while the right hand scale refers to NGC 2023 (*bottom*). The nebular positions measured are (*top*) 30" W 20" N of HD 200775, and (*bottom*) 60" S of HD 37903, where these stars are the illuminating stars of the visual reflection nebulae. Also shown is a curve representing a greybody fit through the 2.2 and 4.8 μm broad band measurements. The color temperature is 1300 K for NGC 7023 (*top*) and 1200 K for NGC 2023 (*bottom*). The wavelength coverage of the 2.2 μm (K), 3.8 μm (L'), and 4.8 μm (M) broad band filters is also shown at the bottom of the figure.



1 Jy
NGC 7023
30" W 20"N
100 mJy
F_ν
10 mJy
NGC 2023
60" S
100 mJy
F_ν
10 mJy
K
L'
M
1 mJy
2.0
3.0
4.0
5.0
λ(μm)

Figure 1

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