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COLORS OF REFLECTION NEBULAE. II. THE EXCITATION OF EXTENDED RED EMISSION

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ABSTRACT

New *BVI* color-difference measurements are reported for the reflection nebulae NGC 7023, NGC 2068, and CED 201. The data are obtained through *BVI* imaging with a CCD detector and are analyzed together with previously published measurements for the reflection nebula NGC 2023. All four nebulae are substantially redder in the (*V*, *I*) range than expected on the basis of dust scattering alone, a result of the presence of extended emission in the *I* band. The relative strength of the *I* excess reaches a maximum in nebular regions where the color in the (*B*, *V*) range is bluest. These facts are interpreted in terms of a model which explains the extended *I* emission as a luminescence process excited by UV radiation from the illuminating star(s). Model fits identify the $1800 < \lambda < 2500$ Å wavelength region of the illuminating star's spectrum as the source of the energy of excitation. It appears possible that the 2200 Å band in the dust-extinction curve is a gate for the excitation energy, and it is likely that the *I* excess emission and the extended near-IR emission recently discovered in reflection nebulae are similar in nature and origin.

Subject headings: interstellar: grains — nebulae: reflection — ultraviolet: general

I. INTRODUCTION

Recently, the reflection nebula NGC 2023 was shown to exhibit an unexpectedly high surface brightness in the $0.65 \leq \lambda \leq 1$ μm spectral region (Witt, Schild, and Kraiman 1984). In the *I* band ($\lambda_{\rm eff} \approx 0.88$ μm; Johnson *et al.* 1966), the surface brightness of this nebula almost certainly is higher than expected from scattering alone, even with a maximum albedo of unity. The extended nature of this excess emission, as well as its relation to the relative intensity of similar extended emission detected at near-IR wavelengths in NGC 2023 by Sellgren, Werner, and Dinerstein (1983) and Sellgren (1984*a*) led to the suggestion that the *I* excess is the high-frequency tail of whatever emission process gives rise to the near-IR extended emission in reflection nebulae.

Three aspects make this possible connection highly significant: (1) the higher the frequency of detected excess emission, the more severe the constraints on the presently favored emission process, which is based on large temperature fluctuations of order 1000 K in micrograins of 10^{-7} cm size (Sellgren 1984*a*); (2) *I* excess emission can be imaged with excellent response and high spatial resolution with optical telescopes and current CCD detectors, allowing an accurate study of the spatial distribution of the excess emission; and (3) thanks to the broad spectral response of CCD detectors, the same object can be observed in the blue part of the spectrum, using the same detector. Since the nebular light in the blue part of the spectrum is the result of scattering, and thus a measure of the transfer of radiation from the illuminating star through the nebula, it becomes possible to relate the relative strength of *I* excess to the quantity and quality of the stellar radiation available for the excitation. In this manner, the source and nature of the energy exciting the *I* excess, and by implication the extended near-IR emission, can be explored.

In the present investigation we have pursued two questions: Is the occurrence of *I* excess emission a common phenomenon among reflection nebulae, not limited to the single previously known case of NGC 2023; and, assuming the source of excitation of the *I* emission to be radiation from the central star, which part of the star's visible-UV spectrum is responsible? To these ends we conducted *BVI* observations of three additional reflection nebulae. Two of these, NGC 7023 and NGC 2068, were reported as exhibiting near-IR extended emission (Sellgren 1984*a*), while the third, CED 201 (Cederblad 1946; Racine 1971), is of interest because of the relatively late spectral type, B9.5 V, of its illuminating star. This severely limits the availability of far-UV radiation, and, with the presence of *I* excess emission in CED 201, would exclude far-UV radiation as the source of excitation. The details of the observations are given in § II, while § III contains an analysis of the nebular color-color diagrams based on a single-scattering approach to nebular colors described in detail elsewhere (Witt 1985).

II. OBSERVATIONS

Observations were made on 1983 December 6 (NGC 2068) and October 13 (NGC 7023, CED 201) with the Whipple Observatory 0.61 m telescope and a thinned (blue-sensitive) RCA CCD detector. The nebular exposures with *B*, *V*, and *I* filters (Johnson *et al.* 1966) were made with the nebulae centered in the frame, and all nebular exposure times were of 10 minutes duration, with the sole exception of the *B* exposure of NGC 2068, which was 20 minutes long. The nebular exposures were bracketed by sky exposures of corresponding length pointed at nearby fields free of nebulosity and by appropriately scaled exposures to yield measurable images of the illuminating stars, since these are all overexposed on the nebular exposures. Tests confirmed the linearity of the shutter timing mechanism over the range from 10 s to 20 minutes, so that the stellar exposures could be scaled accurately to the level of the nebular exposures. Data suitable for the derivation of the profiles of light scattered within the telescope were kindly provided by S. Kent. The nebular intensity was measured in circular fields. The field diameters were chosen so as to produce adequate counts but not to exceed the angular scale over which noticeable color variations could be detected. In some instances, fields were chosen to match in size and location the beams employed in earlier observational programs, e.g., by Racine (1971, CED 201), Witt and Cottrell (1980*a*, NGC 7023), and Zellner (1970, NGC 2068).

The reduction procedure consisted of correction of nebular-intensity measurements for background from sky and detector and of corrections for instrumentally scattered light originating in the centrally located illuminating star. Nebular intensities S were then expressed in units of the flux F_* from the illuminating star observed at Earth, per steradian. The agreement with previously published data was excellent when differences in the filter systems employed were accounted for.

The results are presented in form of color differences, defined as

$$\Delta C(\lambda_1, \lambda_2) = \log \frac{(S/F_*)_{\lambda_1}}{(S/F_*)_{\lambda_2}}, \quad (1)$$

in Tables 1, 2, and 3.

III. ANALYSIS

The presence in a reflection nebula of excess emission in the I band will reduce the color differences $\Delta C(V, I)$ compared to the values expected from scattering alone. Other phenomena affecting the color difference are albedo differences between V and I, the degree to which the illuminating star is embedded into the nebula, the amount of internal extinction occurring within the nebula, the total optical thickness of the nebula, and differences in the scattering-phase function between V and I. The combined result of these effects can be expressed to resonable accuracy by a first-order approximation (Witt 1985):

$$\Delta C(V, I) \approx \log \frac{a(V)\{1 - \exp[-\tau_0(V)]\} \exp[\tau_*(V) - \tau_1(V)]}{a(I)\{1 - \exp[-\tau_0(I)]\} \exp[\tau_*(I) - \tau_1(I)]p(V, I)} . \quad (2)$$

An analogous expression applies to the color difference $\Delta C(B, V)$ with the quantities involved defined as: a, the particle albedo; τ_0, the total optical thickness of the nebula; τ_*, the optical depth in front of an embedded star due to nebular material; τ_1, a suitably averaged optical depth between the star and nebular points along a given line of sight from the observer, and p, the phase contribution ratio, a quantity of order unity.

TABLE 1

COLOR DIFFERENCES IN NGC 7023

Position[a]		Color Differences	
North-South	East-West	$\Delta C(B, V)$	$\Delta C(V, I)$
35″N	43″W	−0.12	−0.25
20 N	55 W	−0.04	−0.19
21 N	37 W	−0.01	−0.10
33 N	58 W	+0.03	−0.21
25 N	107 W	+0.14	−0.16
61 N	24 W	−0.06	−0.14
26 N	25 E	+0.11	−0.10
20 N	39 E	+0.13	−0.11
29 S	75 E	+0.21	−0.16
42 S	7 W	+0.10	+0.04
54 S	18 W	+0.09	+0.04
71 S	11 W	+0.05	−0.08
73 S	36 W	+0.05	−0.12
40 S	23 W	+0.32	−0.36
22 S	31 W	+0.09	−0.20
134 S	25 E	+0.12	+0.04
31 N	124 E	+0.04	−0.27
30 N	...	+0.10	−0.11
30 S	...	+0.33	−0.31
50 S	...	+0.12	−0.07
75 S	...	+0.07	−0.05
100 S	...	+0.10	−0.07
125 S	...	+0.13	−0.05
...	50 E	+0.23	−0.34
...	75 E	+0.25	−0.34
...	100 E	+0.24	−0.36
...	125 E	+0.23	−0.32

[a] Relative to HD 200775. Beam 11″.7 diameter for fields with north-south and east-west offset, Beam 50″ diameter for fields with offset in only one dimension.

TABLE 2

COLOR DIFFERENCES IN CED 201

Position[a]		Color Differences[a]	
North-South	East-West	$\Delta C(B, V)$	$\Delta C(V, I)$
27″S	...	0.11	−0.31
27 N	...	0.04	−0.05
...	27″E	0.07	−0.08
...	27 W	0.07	−0.47
54 N	27 E	0.02	−0.16
...	54 E	0.06	−0.05
...	81 E	0.11	−0.11
...	108 E	0.00	−0.24
...	135 E	0.08	−0.21

[a] Relative to illuminating star BD +69°1231, beam size 19″.0.

TABLE 3

COLOR DIFFERENCES IN NGC 2068

Position[a]		Color Differences[a]	
North-South	East-West	$\Delta C(B, V)$	$\Delta C(V, I)$
7″N	56″W	0.22	0.40
12 N	40 W	0.20	0.31
25 N	26 W	0.16	0.18
15 N	25 W	0.19	0.16
15 N	11 W	0.18	0.14
4 S	26 W	0.29	0.45
18 S	10 W	0.31	0.44
15 S	1 W	0.23	0.17
7 S	15 E	0.31	0.45
7 N	11 E	0.24	0.23
17 N	18 E	0.22	0.33
23 N	48 E	0.27	0.31
4 S	56 E	0.34	0.59
34 S	72 E	0.30	0.53
56 S	81 E	0.33	0.55
153 S	39 E	0.32	0.56
48 S	162 E	0.32	0.54
47 S[b]	64 E	0.31	0.52
115 S[c]	10 E	0.29	0.48
40 S	60 E	0.35	0.44

[a] Relative to the illuminating star HD 38563N. Beam size 11″.7, unless otherwise noted.
[b] Beam size 29″.3.
[c] Beam size 32″.2.

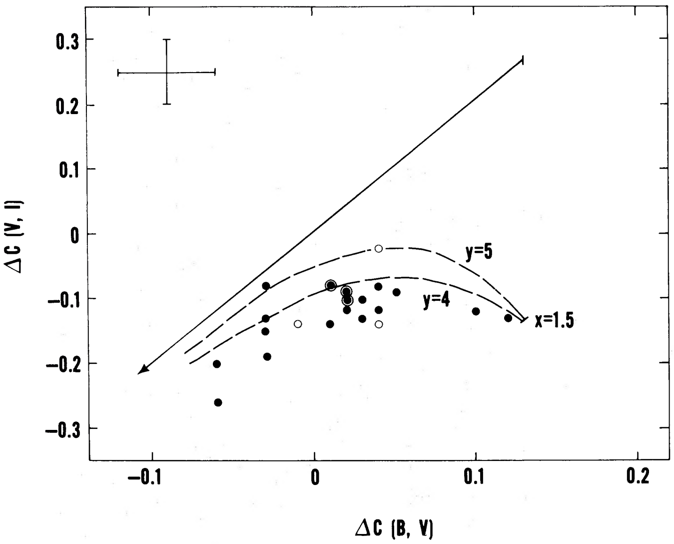

FIG. 1.—Color-color diagram for NGC 2023. Data are based on Table 3A (*open circles*) and Table 3B (*filled circles*) of Witt, Schild, and Kraiman (1984). Model parameters are $\tau_*(B) = 1.53$, $\tau_*(V) = 1.23$, $\tau_*(I) = 0.615$. The cloud is assumed to be optically thick, $\tau_0(V) = 32$. Other parameters are discussed in the text.

In Figure 1 we present a $\Delta C(B, V) - \Delta C(V, I)$ color-color diagram for NGC 2023, based on our published surface-brightness measurements (Witt, Schild, and Kraiman 1984). The solid line is the color-color relationship predicted by the first-order approximation under the assumption of a constant albedo and a constant phase function ($p = 1$) over the B, V, I range. The wavelength dependence of the optical depths was patterned after the results of Lee (1968) and de Boer (1983) for the extinction law for HD 37903. The arrow indicates the direction of increasing values of τ_1. We find that the measured values of $\Delta C(B, V)$ agree well with the predicted range for that color difference, but the $\Delta C(V, I)$ data indicate that the nebula is substantially brighter in I than anticipated, in agreement with our earlier finding. The data also show clearly that *the deviation from the predicted* $\Delta C(V, I)$ *color difference is larger, the larger* (*bluer*) *the* $\Delta C(B, V)$ *color difference is.*

This result is most easily interpreted if one considers that the range of $\Delta C(B, V)$ values results from differences in internal reddening of nebular radiation. Thus, the largest $\Delta C(B, V)$ values in a given nebula arise where the reddening of stellar radiation before and after scattering is at a minimum. We conclude, therefore, that the maximum relative strength of the I excess occurs where radiation arriving from the illuminating star is spectrally least altered. This is consistent with an interpretation whereby the nebular excess emission in I is caused by excitation by stellar UV radiation. We can formally introduce such a process in our first-order approximation for the color difference $\Delta C(V, I)$ by letting

$$\Delta C(V, I) \approx \log \frac{a(V)\{1 - \exp[-\tau_0(V)]\}}{a(I)\{1 - \exp[-\tau_0(I)]\}} \times \frac{\exp[\tau_*(V) - \tau_1(V)]}{\exp[\tau_*(I)][e^{-\tau_1(I)} + xe^{-y\tau_1(I)}]p(V, I)} . \quad (3)$$

Here, x is the ratio of excess emission in I to scattered radiation in I for unreddened exciting radiation, and y is the scaling factor between the optical depth τ_1 at I and the optical depth $\tau_1(\mathrm{UV}) = y\tau_1(I)$ for radiation causing the excitation. The added term in equation (3) allows us to introduce *ad hoc* an excess of radiation at I that has a different scaling law with distance from the exciting star than the I radiation from the star.

In Figure 1 we show as dashed curves two color-color lines predicted with $y = 4$ and $y = 5$ for $x = 1.5$. The $y = 4$ model fits the data surprisingly well, if one considers that additional reddening of nebular radiation *after* scattering will displace points in a direction parallel to the solid reddening line in Figure 1, an effect not explicitly included in equation (3). Certainly, for NGC 2023, $y \leq 5$.

Figure 2 shows our new data for NGC 7023 together with the color-color line for scattering with albedo ratios $a(B)/a(V)/a(I) = 1/1/1.25$ and constant phase function (*solid*) and two models allowing for UV-excited excess emission in I. It appears that NGC 7023 exhibits an I excess with very similar characteristics to that observed in NGC 2023. A reasonable solution is $x = 4.5$ and $y \leq 7$, with $y = 5 \pm 1$ being a probable fit.

The UV extinction curves for HD 37903 (NGC 2023) (de Boer 1983; Witt, Bohlin, and Stecher 1984) and for HD 200775 (NGC 7023) (Witt and Cottrell 1980*b*; Walker *et al.* 1980; Witt, Bohlin, and Strecher 1981) have been studied extensively, and it is therefore possible to determine the wavelength range of the UV photons causing the excess emission in the I band. For HD 37903, we have from de Boer (1983) $R_V = A_V/E(B-V) = 4.1$ and from Lee (1968) $E(V-I)/E(B-V) = 1.81$. This yields $A_I/E(B-V) = 2.29$, and with $y \approx 4$ for the best fit to the data in Figure 1, we find $A_{\mathrm{UV}}/E(B-V) = 2.9y = 9.16$, which corresponds in the notation of normalized UV extinction curves to $E(\mathrm{UV}-V)/E(B-V) = 5.06$. The results of Witt, Bohlin, and Stecher (1984) for HD 37903 indicate that this level of extinction is reached only in the 2200 Å band and at $\lambda \leq 1340$ Å.

For HD 200775 there is no indication of abnormal reddening in the near-IR, and we adopt standard values $R_V = 3.1$ and $E(V-I)/E(B-V) = 1.60$; hence $A_I/E(B-V) = 1.50$. The fit to the data in Figure 2 yielded $y = 5 \pm 1$, and thus $A_{\mathrm{UV}}/E(B-V) = 7.5 \pm 1.5$. This results in $E(\mathrm{UV} - V)/E(B-V) = 4.4 \pm 1.5$. Unfortunately, the level of UV extinction in HD 200775 is uncertain, because intrinsic reddening contributes to the color excess $E(B-V)$ of this Be star. If the actual UV extinction curve for HD 200775 is intermediate to the two extreme cases presented by Witt, Bohlin, and Stecher (1981), the condition $E(\mathrm{UV}-V)/E(B-V) = 4.4 \pm 1.5$ is again first satisfied in the 2200 Å band and then at $\lambda \leq 1500$ Å.

The data for CED 201, with its illuminating star BD $+69°1231$ a B9.5 V star, are of crucial importance in deciding whether the excitation of the excess emission in I occurs through photons absorbed in the 2200 Å band or through far-UV photons with $\lambda < 1500$ Å. The data are shown in Figure 3.

The color-color lines for constant albedo and phase function for scattering only (*solid line*) and including extended I emission (*dashed curves*) are computed on the assumption that the observed reddening $E(B-V) = 0.21$ of BD $+69°1121$ is a result of the star being immersed in the nebula. The presence of a strong I excess is apparent, and the relatively low temperature of the illuminating star makes excitation by radiation with $\lambda < 1500$ Å unlikely. The analysis of available *IUE* data on BD $+69°1231$ shows this star to exhibit a stronger than average 2200 Å band (Bohlin 1982, private communication). So far, CED 201 has not been studied in the 1 μm $< \lambda <$ 5 μm

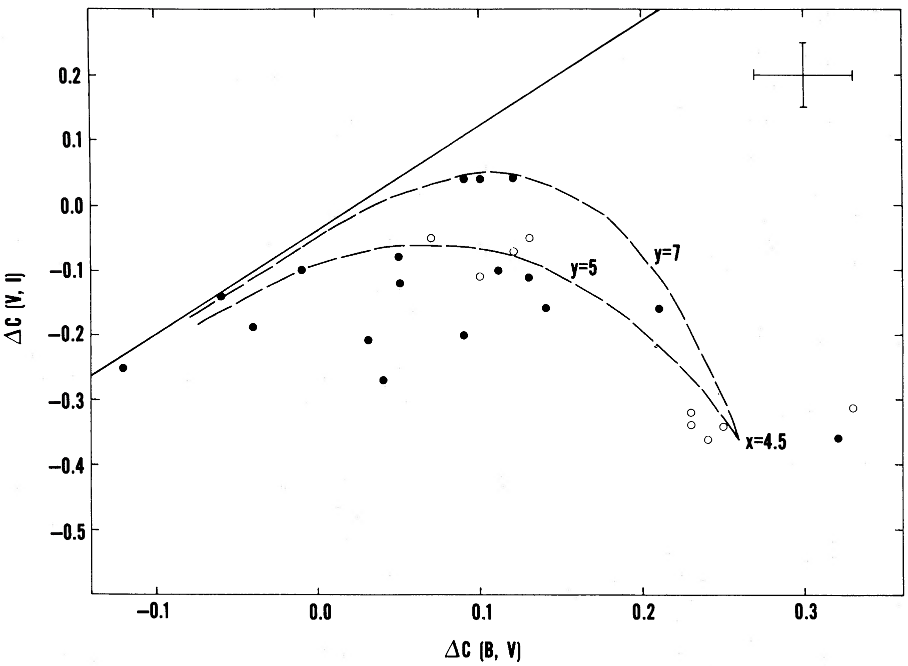

FIG. 2.—Color-color diagram for NGC 7023 (Table 1). Open circles represent 50″ fields east and south of HD 200775, filled circles are 11″.7 fields. Model parameters: $\tau_*(B) = 2.37$, $\tau_*(V) = 1.79$, $\tau_*(I) = 0.87$, $\tau_0(B) = 4.32$, $\tau_0(V) = 3.24$, $\tau_0(I) = 1.59$, $a(V)/a(I) = 0.8$.

spectral region, but, given the strong presence of *I* excess emission and the good spatial correlation of the *I* excess and the near-IR emissions in NGC 2023 and NGC 7023, it appears to be a strong candidate for exhibiting the near-IR emission as well. The combination of the results for NGC 2023 and NGC 7023 with those for CED 201 leads us to the conclusion that photons in the 1800 Å $< \lambda <$ 2500 Å region, probably absorbed through the broad 2200 Å extinction band, are the likely source of excitation of extended *I* emission in these nebulae.

In Figure 4 the data for NGC 2068 are displayed. Data from fields with offsets less than 40″ from the illuminating star, HD 38563N, are shown as circled dots. The two solid lines are color-color predictions for constant phase function and constant albedo (*lower*) and for an albedo ratio $a(V)/a(I) = 1.10$ (*upper curve*). The open square represents our color measurements at the 2.2 μm intensity peak in NGC 2068 reported by Sellgren (1984*a*). While NGC 2068 is one of the bluest reflection nebulae known, the presence of excess emission in *I* in the vicinity of the illuminating star is evident. The illuminating star

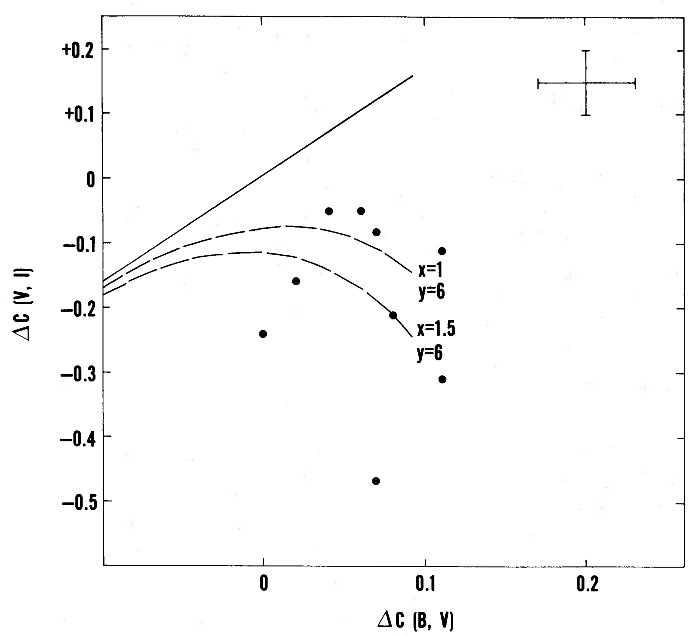

FIG. 3.—Color-color diagram of CED 201 (Table 2). Model parameters are: $\tau_*(B) = 0.86$, $\tau_*(V) = 0.65$, $\tau_*(I) = 0.30$, $\tau_0(B) = 12.15$, $\tau_0(V) = 9.15$, $\tau_0(I) = 4.29$.

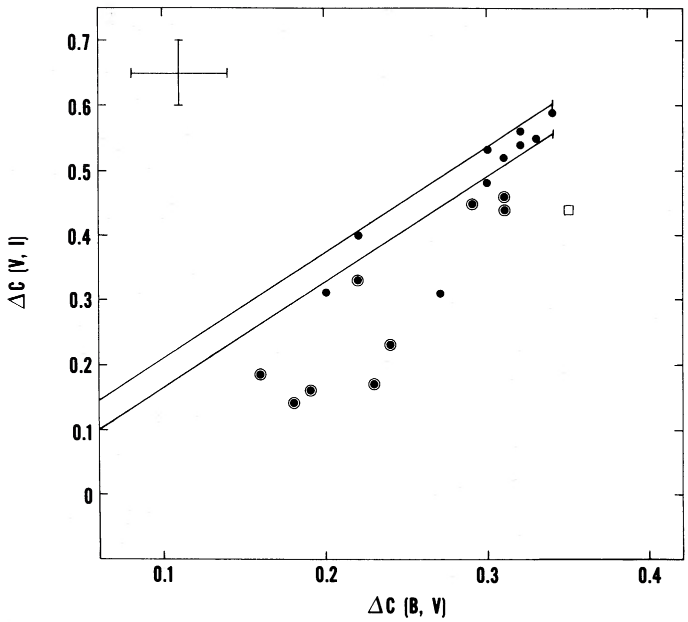

FIG. 4.—Color-color diagram for NGC 2068 (Table 3). Model parameters are $\tau_*(B) = 3.20$, $\tau_*(V) = 2.42$, $\tau_*(I) = 1.14$ with an optically thick cloud, $\tau_0(V) = 30$. The circled points are fields within 40″ of the illuminating star, HD 38563N.

of this nebula, HD 38563N [$E(B-V) = 1.42$], is affected by heavy local obscuration toward the observer, causing severe reddening for the stellar as well as the nebular radiation originating near the star. The more distant blue regions to the south of HD 38563N, apparently, are being illuminated by relatively unreddened stellar radiation, and there is little subsequent reddening, either. This interpretation of the unusual nebular structure is supported by surface brightness and polarization studies by Elvius and Hall (1966), Glushkov (1965), and Mannion and Scarrott (1984). Since our simple model for the production of excess emission in I (eq. [3]) does not include a provision for spatially variable secondary reddening, no attempt has been made to achieve a fit to the NGC 2068 data. It appears that the characteristic pattern of I excess with color difference $\Delta C(B, V)$ is most clearly observed in symmetric reflection nebulae with a centrally embedded star, such as NGC 2023 and NGC 7023. However, the $\Delta C(V, I) - \Delta C(B, V)$ color-difference approach has been most successful in revealing the presence of extended excess emission in the I band in all four reflection nebulae studied so far.

In this study, the I excess has been detemined relative to scattering models wherein the dust albedo at I was assumed to at least equal the albedo at V. One should note that predictions from the frequently referenced model for interstellar grains of Mathis, Rumpl, and Nordsieck (1977) indicate a substantially *lower* albedo at I relative to V (White 1979; Draine and Lee 1984), in which case the relative magnitude of the I excess would be even greater. However, if one were to require that the I excess be a result of enhanced scattering efficiency at I, a combination of higher albedo plus phase function advantage, the following factors over V would be needed: 2.5 for NGC 2023, 5.5 for NGC 7023, 2.5 to 3.9 for CED 201, and 1.5 for NGC 2068. Given that at V the dust albedo is of order 0.6–0.7 (FitzGerald, Stephens, and Witt 1976) and that the phase function is strongly forward-directed, of great advantage in nebulae with embedded stars, it appears fairly certain that the I excess of the magnitude found in NGC 2023, NGC 7023, and CED 201 requires a nonscattering emission process. The fact that a simple model assuming excess I emission resulting from excitation by stellar radiation in the $1800 < \lambda < 2500$ Å provides good fits to the observed pattern of the I excess lends further support for this conclusion.

It is finally of interest to examine the energy balance between photons absorbed in the 1800–2500 Å band and excess emission in the I band (7200–9000 Å). If one represents the illuminating stars in NGC 2023, 2068, and 7023 by atmosphere models for $T_{\rm eff} = 20{,}000$ K, $\log g = 4.0$ (Kurucz, Peytremann, and Avrett 1974) and if one assumes that 66.5% of the radiation in the 1800–2500 Å band is absorbed, the excess emission in the I band represents less than 5% of this absorbed energy for $x = 1.5$, about 14% for $x = 4.5$ in the case of NGC 7023. This estimate is based on the assumption that 39% of the star's luminosity in the I band is scattered in these optically semi-thick nebulae.

The most restrictive case is that of CED 201. Assuming that the star can be represented by a $T_{\rm eff} = 10{,}000$ K, $\log g = 4.0$ atmosphere, we find that $x = 1.5$ corresponds to 50% of the energy absorbed in the 1800–2500 Å band being reemitted in the I band. These arguments demonstrate that there is sufficient energy absorbed in the band dominated by the 2200 Å feature to power the excess emission in the I band, but they do not rule out other energy channels.

Independent confirmation of nonscattering emission in the I band should be sought through observations of the wavelength dependence of polarization of reflection nebulae. Existing data (e.g., Elvius and Hall 1966; Zellner 1970) for the blue-visible region show the polarization to increase with increasing wavelength, except when backscattering is involved. We suggest that nebular regions with large I excesses will exhibit a proportionally reduced polarization in I, when compared with levels anticipated on the basis of scattering alone, because we see no reason to assume that the excess radiation should be polarized. Sellgren (1984*b*) has presented preliminary evidence which shows that the predicted behavior occurs at $\lambda = 2.2\ \mu$m in NGC 7023.

IV. SUMMARY

New color-difference data for the reflection nebulae NGC 7023, NGC 2068, and CED 201, covering the *B*, *V*, *I* spectral region, have been obtained through direct imaging with a CCD detector. The analysis of these data, together with those of the previously observed nebula NGC 2023, has led to the following results:

1. All four nebulae exhibit substantial amounts of extended emission in the *I* band beyond what is explainable simply by dust scattering.

2. In NGC 2023 and NGC 7023 the relative strength of the *I* excess reaches a maximum in the bluest nebular regions, as measured by the color difference $\Delta C(B, V)$. In NGC 2068 there is a pronounced maximum in the relative strength of the *I* excess in the vicinity of the illuminating star.

3. A simple color-color model assuming that excess *I* emission in reflection nebulae is a result of excitation by UV radiation from the illuminating stars successfully explains the observations.

4. The fit of the model to our data suggests that mid-UV radiation ($1800 < \lambda < 2500$ Å) is responsible for the excitation of excess *I* emission. This result is further supported by the positive detection of excess *I* emission in CED 201, a nebula illuminated by a B9.5 V star. The role of the 2200 Å hump in the extinction curve due to dust should be considered as a possible energy channel. In all four nebulae, the energy absorbed in the 2200 Å feature is more than sufficient to power the observed *I* excess.

5. In NGC 2023, the close relationship between the *I* excess and the extended near-IR emission discovered by Sellgren *et al.* has already been demonstrated. The discovery of *I* excess emission in NGC 2068 and NGC 7023, the other two nebulae with known near-IR emission, further strengthens this association, and in fact suggests a common nature and origin.

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