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DETECTION OF SCATTERING IN THE 2175 Å INTERSTELLAR BAND

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ABSTRACT

Spectrophotometric observations of two reflection nebulae and their illuminating stars obtained with the *International Ultraviolet Explorer Satellite* have provided the first evidence for the presence of a scattering contribution to the 2175 Å interstellar extinction band. Lower than normal far-UV extinction for the stars embedded in the nebulae indicates that the nebulae have a dust particle size distribution that is dominated by larger particles. The strength of the 2175 Å band is larger than normal in both cases. The scattering is found to dominate the long-wavelength wing of the band, without shifting the central wavelength of the band by more than 20 Å toward longer wavelengths. We take these observations to indicate that the solid particles responsible for the 2175 Å band can be considerably larger than the Rayleigh limit in some interstellar locations. The absence of a notable shift in the central wavelength of the band in such large particles presents a new severe constraint for models of interstellar grains.

Subject headings: interstellar: grains — interstellar: matter — nebulae: reflection

I. INTRODUCTION

The broad interstellar band near 2175 Å, first observed by Stecher (1965, 1969), is the most prominent and most universally present feature in the wavelength dependence of extinction caused by interstellar dust. Most notable among the observed characteristics of the 2175 Å band is the near constancy of the central wavelength (Savage 1975; Gürtler *et al.* 1982; Fitzpatrick and Massa 1986). While the band strength is generally well-correlated with the visual color excess $E(B - V)$, variations in the normalized strength of the 2175 Å feature by up to a factor of 2 or 3 for different lines of sight in the Galaxy are not uncommon (Witt, Bohlin, and Stecher 1984; Fitzpatrick and Massa 1986). A true variability of the width of the band has also been confirmed by Fitzpatrick and Massa.

Observations of the diffuse galactic light (Lillie and Witt 1976; Morgan, Nandy, and Thompson 1976) have shown that the albedo of interstellar dust undergoes a broad minimum near 2175 Å, consistent with the suggestion that the 2175 Å band is entirely due to absorption. Spectrophotometric observations of several reflection nebulae (Andriesse, Piersma, and Witt 1977; Witt *et al.* 1982; Witt, Bohlin, and Stecher 1986) have so far supported this assessment.

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There is no generally accepted identification of the 2175 Å feature. The remarkable constancy of the central wavelength of the band and its absorption nature have been combined, however, to support various dust models which attribute the 2175 Å band to grains (e.g. graphite, amorphous carbon, or MgO), sufficiently small so as to be operating within the Rayleigh limit (particle radius $\ll$ 2175 Å) (Mathis, Rumpl, and Nordsieck 1977; Hong and Greenberg 1980; Draine and Lee 1984; Hecht 1986; MacLean, Duley, and Millar 1982).

In this *Letter* we are reporting the first cases where scattering has been found in association with the 2175 Å feature.

II. OBSERVATIONS

Reflection nebulae with embedded illuminating stars allow the simultaneous study of extinction and scattering of starlight by dust grains in a single cloud. We have used the *IUE* satellite (Boggess *et al.* 1978) to obtain low-resolution observations of the ultraviolet energy distributions of the star BD +69°1231 [B9.5 V, $E(B - V) = 0.19$] and the reflection nebula CED 201 associated with it. A second similar data set consisted of our *IUE* observations of the star HD 38087 [B5 V, $E(B - V) = 0.24$; Witt, Bohlin, and Stecher 1984], supplemented by *IUE* data for the associated reflection nebula IC 435, observed by P. Benvenuti, obtained from the *IUE* archives. All data are now in the public domain in the *IUE* archives. A complete list of the *IUE* image numbers of the data used in this study is available from the authors upon request.

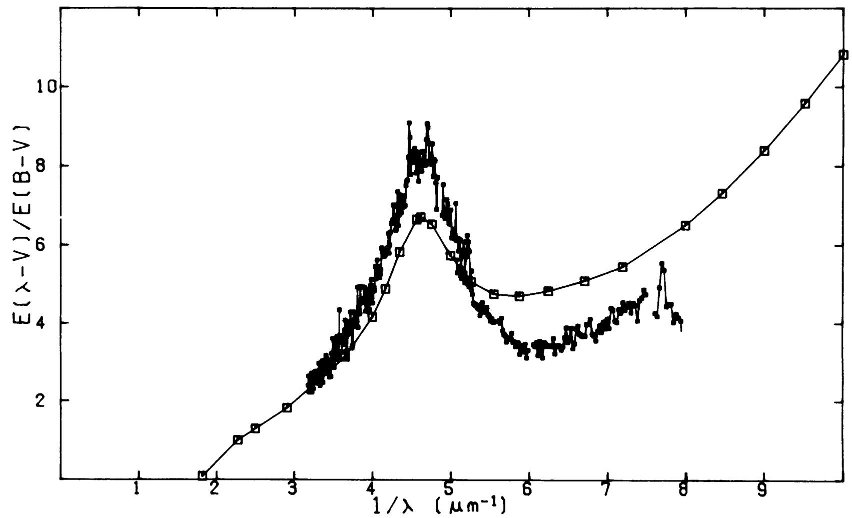

FIG. 1.—The normalized extinction curve for BD +69°1231, the illuminating star of the reflection nebula CED 201. The continuous curve with squares is the average galactic extinction curve of Seaton (1979), shown for comparison.

a) *Extinction*

We matched the UV spectrum of BD + 69°1231 with that of the unreddened B9.5 V star HD 222661 (ω^2 Aqr) and derived the UV extinction curve through the pair method (Bohlin and Savage 1981). The result is shown in Figure 1, together with the average galactic extinction curve of Seaton (1979) for comparison. Two outstanding characteristics of the extinction curve of BD +69°1231 are the exceptional strength of the 2175 Å band and the depressed level of extinction in the $5 < \lambda^{-1}$ (μ^{-1}) < 8 range. The central wavelength of the observed 2175 Å band agrees with that of the average curve.

Two arguments suggest to us strongly that the unusual extinction of BD +69°1231 is caused predominantly by dust located in the immediate vicinity of BD +69°1231, in the cloud identified with the reflection nebula CED 201. The first is that the extinction curve of BD +69°1232, a B8.5 V star located 7′ south of BD +69°1231 at approximately the same distance, exhibits a 2175 Å band of entirely normal strength. The second argument is that the high surface brightness of CED 201 and its steep intensity gradient at visible wavelengths can be explained only if the illuminating star is embedded with an optical depth corresponding to the entire observed color excess $E(B - V) = 0.19$ of BD +69°1231 (Witt et al. 1986, in preparation).

The extinction curve for our second program star, HD 38087, has been published by us earlier (Witt, Bohlin, and Stecher 1984). This curve is similar to the one for BD +69°1231 shown in Figure 1 in that it exhibits a 2175 Å band with a strength 28% above average and far-UV extinction at 1250 Å 37% below the galactic average. A separate analysis of HD 38087 by Fitzpatrick and Massa (1986) yields a strength of the 2175 Å band 29% above the mean, with its central wavelength displaced to 2193 Å. Among 45 individual stars examined by these authors, the displacement of the peak extinction in HD 38087 toward longer wavelengths by 18 Å is the largest value found.

b) *Scattering*

The spectra of CED 201 and IC 435 were obtained with the large *IUE* entrance apertures (4.9×10^{-9} sr) at approximately 20″ offsets NE and NW from the respective illuminating stars. We corrected the nebular observations for instrumentally scattered light due to the nearby illuminating star by using the scattered light corrections derived by Witt *et al.* (1982). The instrumentally scattered light amounted to approximately 10% of the nebular signal. Corrections were also applied for the known nonlinearity errors for the LWR and SWP cameras of the *IUE* (Oliversen 1984) for the case of nonoptimum weak exposures in the presence of high background levels. A major error source for fluxes derived from underexposed *IUE* spectra arises from the variation of the background over the *IUE* images. In the case of CED 201 we derived nebular fluxes with three different pairs of detector regions adjacent to the spectra as backgrounds. The resulting standard deviations shown in Figure 2*a* are computed for these three net nebular intensities S in each 100 Å bin. In Figure 2*b* we show the corresponding fluxes F_* for the illuminating star BD +69°1231, and in Figure 2*c*, the ratio of nebular intensity to stellar flux. The corresponding data for IC 435 are shown in Figures 3*a*, 3*b*, and 3*c*.

The most remarkable result common to the data for both nebulae is the fact that the normalized nebular intensities S/F_* show distinct peaks at a wavelength *longward* of the central wavelength of the 2175 Å band, which is indicated by arrows in Figures 2*c* and 3*c*. The wavelength region immediately surrounding the wavelength of maximum extinction, i.e., from 2250 Å to 2100 Å, is characterized by a very rapid decline of $\log(S/F_*)$ as one proceeds from longer to shorter wavelengths. The nebular data at 2000 Å may still be affected by a residual nonlinearity, and reduced importance should be attached to the pronounced minimum in Figure 2*c*. The wavelength regions outside the range of the 2175 Å band, i.e., 2800–3200 Å and 1300–1800 Å, show variations in

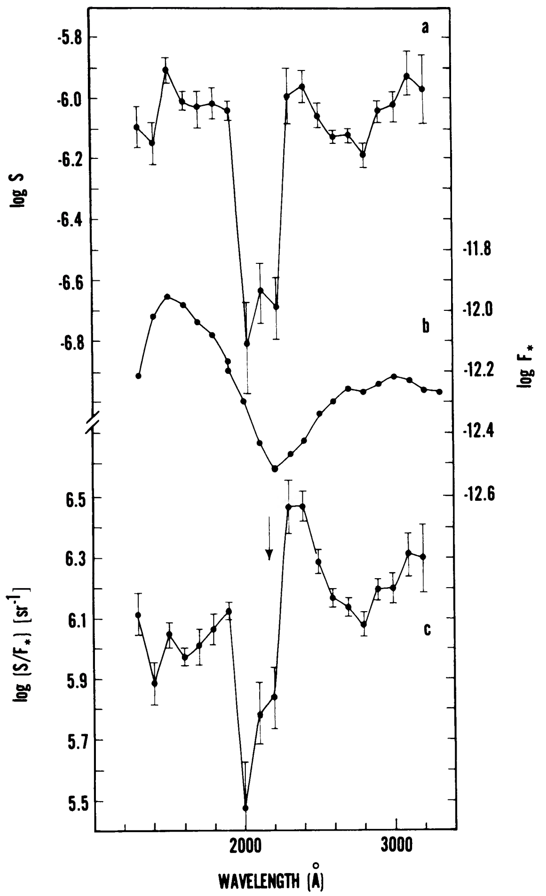

FIG. 2.—(a) The nebular intensity S of CED 201 (20″ NE of BD +69°1231) derived from *IUE* images SWP 26053 and LWR 17725. (b) Flux distribution of BD +69°1231. The applicable scale is on the right-hand side. (c) The relative intensity S/F_* for CED 201; the arrow indicates the central wavelength of the 2175 Å band in BD +69°1231.

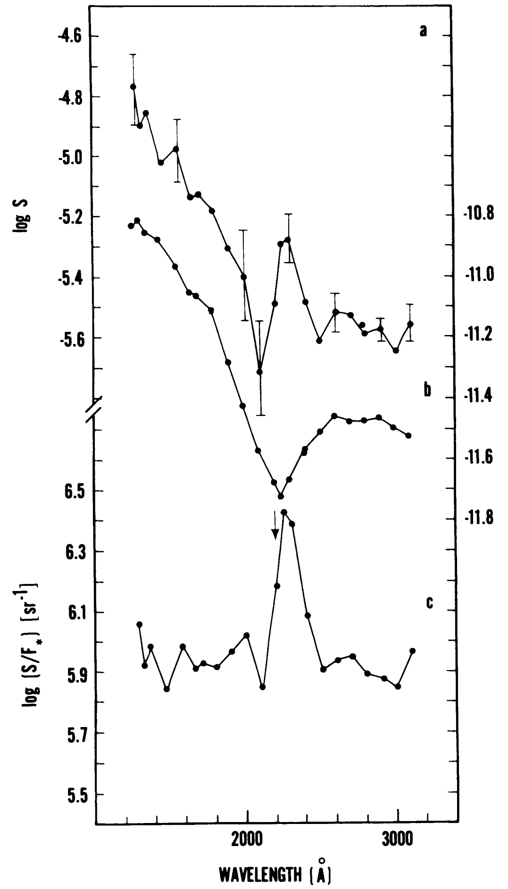

FIG. 3.—(a) The nebular intensity S of IC 435 (20″ NW of HD 38087) derived from *IUE* images SWP 9802 and LWR 8517. (b) Flux distribution of HD 38087. (c) The relative intensity S/F_* for IC 435; the arrow shows the position of the central wavelength of the 2175 Å band in HD 38087.

$\log(S/F_*)$ which seem to be continuous extensions of each other.

III. DISCUSSION

a) *Interpretation of Observations*

While a quantitative analysis of the results displayed in Figures 2 and 3 requires a full treatment of the radiative transfer involved, certain qualitative conclusions can be drawn at this time. Let us assume that the directly observed stellar radiation and the scattered nebular light prior to and following scattering suffer approximately similar amounts of extinction. We then estimate the increase of the total extinction cross section in going from 2700 Å to 2300 Å for the two nebulae to be between 50% (BD +69°1231) and 60% (HD 38087), derived from the respective normalized extinction curves. The corresponding increases in the normalized nebular intensities S/F_* deduced from Figures 2 and 3 amount to factors of 2.1 (CED 201) and 2.8 (IC 435). We conclude from these facts that the long-wavelength side of the 2175 Å band in these two clouds is associated with strong scattering, accompanied by an increase in the particle albedo by from 40% (CED 201) to 75% (IC 435) over the limited wavelength region from 2700 Å to 2300 Å. This is quite in contrast to results for the general diffuse interstellar medium, where the dust albedo has been found to decline by about 30% over the same wavelength interval (Lillie and Witt 1976).

Our results also indicate that shortward of 2250 Å, the 2175 Å extinction band becomes quickly dominated by absorption. For CED 201, the total extinction cross section at 2100 Å is still 65% above the value of 2700 Å, while in Figure 2c $(S/F_*)_{2100}$ is lower than the corresponding value at 2700 Å by a factor of more than 2. This implies that the albedo at 2100 Å can at best be one-third that of the albedo at 2700 Å. The corresponding value of the albedo reduction in IC 435 between 2700 Å and 2100 Å is one-half, as derived from Figure 3c.

In both nebulae the wavelength region shortward of 1800 Å is characterized by an extinction cross section comparable to or slightly lower than that at 2700 Å. Figures 2 and 3 show that similar relationships exist between the corresponding $\log(S/F_*)$; hence, the albedo in the far-UV ($\lambda < 1800$ Å) must be quite similar to the value at 2700 Å. Albedo comparisons extended over longer wavelength regions may have to be modified, if the phase function of scattering is wavelength dependent in these two nebulae.

b) Model Considerations

The discovery of enhanced scattering associated with the 2175 Å extinction band provides a new constraint for models of interstellar grains in general and of the 2175 Å agent, in particular. The very observation of band scattering with the characteristics described in § III*a* implies that *the 2175 Å band is produced by solid particles*. The deduced albedo variations across the 2175 Å band appear to be a reflection of the wavelength dependence of the real part of the index of refraction expected in general for a spectral region dominated by an absorption band. For CED 201 and IC 435, the observations imply further that the particles responsible for the 2175 Å feature are sufficiently large so that *the Rayleigh approximation is no longer applicable* (Bohren and Huffman 1983), because only as the particle size is no longer small compared to the wavelength will scattering become appreciable. The conclusion develops particular impact through the associated fact that the central wavelengths of the extinction band features in BD +69°1231 and HD 38087, the two stars associated with CED 201 and IC 435, respectively, show little or no shift from the normally observed central wavelength of the 2175 Å band (Fitzpatrick and Massa 1986).

Stecher and Donn (1965), Gilra (1972), and many others suggest that small graphite grains are the cause of the 2175 Å band. If graphite grains can be spherical and as long as their radii are almost exactly 200 Å, a surface plasmon resulting in almost pure absorption will appear in such particles at a wavelength of 2190 Å, near where the real part of the dielectric function goes through the value $\varepsilon_1 = -2$ (Gilra 1972; Draine 1985). In graphite this occurs at $\lambda_0 = 2205$ Å. As the particle size is increased beyond the Rayleigh limit, scattering begins to dominate the side of the band with $\lambda > \lambda_0$, resulting in a shift of the peak wavelength. For example, appreciable scattering begins to appear for graphite grains of radius 0.03 μm with albedo $a(2000$ Å$) = 0.30$ and $a(2381$ Å$) = 0.43$, with the extinction peak shifted to $\lambda = 2305$ Å (Wickramasinghe 1973). This shift in resonance peak wavelength associated with increasing particle size and with rising importance of scattering is not specific to graphite alone but is a general characteristic of plasma resonances in solids, resulting from the manner in which the real and the imaginary components of the index of refraction vary across such resonances (e.g., Christy 1972). Results for gold shown by van de Hulst (1957) are particularly instructive.

The wavelength dependence of the grain albedo has been calculated for the frequently used dust model of Mathis, Rumpl, and Nordsieck (1977) by White (1979) and by Draine and Lee (1984). The predicted albedo variation is a gradual decline from 0.66 at 2700 Å to 0.60 at 2300 Å to 0.50 at 2160 Å to 0.46 at 1700 Å, which is not in agreement with the behavior deduced in § III*a*. The comparison may not be justified, however, because the model of Mathis, Rumpl, and Nordsieck (1977) was designed to match average galactic conditions, not the somewhat anomalous extinctions found in CED 201 and IC 435.

Increased particle size for the 2175 Å extinction agent, leading to observable scattering *without* a shift of the band center to longer wavelengths, has another important consequence for models. In the size regime just beyond the Rayleigh limit, the extinction efficiency of grains increases rapidly with size. The large range of 2175 Å band strengths observed in the Galaxy (Witt, Bohlin, and Stecher 1984; Fitzpatrick and Massa 1986) could be a result of a range of particle sizes rather than a result of varying abundance ratios of different particle components. In this context we note that the UV extinction curves of BD +69°1231 and HD 38087, aside from having exceptionally strong 2175 Å bands, have the overall characteristics of larger than average particle environments.

IV. SUMMARY

In two reflection nebulae, characterized by dust exhibiting exceptionally strong 2175 Å bands but otherwise rather weak far-UV extinction, we have found observational evidence which suggests that the 2175 Å band extinction has a strong scattering component. In these two cases where larger particles dominate the size distribution function, the 2175 Å band strength is larger than normal. A remarkable fact is that the enhanced relative abundance of 2175 Å band particles larger than the Rayleigh limit is not accompanied by a significant shift of the band peak to longer wavelengths. The larger shift of our two cases amounts to 18 Å. These facts place new constraints on models for interstellar dust grains and, in particular, suggest that much of the variation in the 2175 Å band strength between different lines of sight may be a size effect.

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