THE ASTROPHYSICAL JOURNAL, 446:L97–L100, 1995 June 20

SCATTERING PROPERTIES OF THE DUST IN THE REFLECTION NEBULA IC 435

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Received 1995 March 9; accepted 1995 April 13

ABSTRACT

New *IUE* observations of the reflection nebula IC 435 are presented, and the scattering properties of the nebular dust grains are derived. Previous studies of this nebula suggested the presence of enhanced scattering in the 2175 Å interstellar extinction bump, which the new data do not confirm. The UV observations plus optical data from the literature determine the most likely star-nebula geometry, the nebular dust density distribution, and the values of the albedo and the phase function asymmetry for the dust grains. The results show a broad minimum for the albedo around 2300 Å followed by rising values in the far-UV, up to $a \simeq 0.75$–0.8. The phase function for the nebular grains tends to be forward-scattering in the UV, with values for the phase function asymmetry rising from $g \simeq 0.60$ at 3000 Å to $g \simeq 0.75$ around 1500 Å.

Subject headings: dust, extinction — ISM: individual (IC 435) — reflection nebulae — ultraviolet: ISM

1. INTRODUCTION

Reflection nebulae represent important astrophysical laboratories for studying the scattering properties of the interstellar dust grains as a function of wavelength. At ultraviolet (UV) wavelengths the illumination of the nebula often arises from a single star, implying that the geometrical distribution of the dust around the star can be constrained. Therefore, reflection nebulae are particularly suitable for investigations of the optical properties of the dust grains in the UV.

The study of the UV characteristics of dust scattering in the Galaxy is essential to our understanding of the characteristics of dust obscuration in external galaxies. In particular, one of the unsolved puzzles is the apparent absence of the 2175 Å dust bump in the UV spectra of reddened starburst galaxies (Calzetti, Kinney, & Storchi-Bergmann 1994). The interpretation of this finding is complicated by the many factors contributing to the extragalactic obscuration curve, which include the geometrical effects due to the dust-stars-gas distribution, and, possibly, the optical properties and the composition of dust. Therefore, the properties of the 2175 Å bump need to be fully investigated as a function of the environment in order to understand the observed absence in external galaxies.

Since its discovery (Stecher 1965), the 2175 Å bump has been attributed to absorption by dust grains which are sufficiently small to be operating in the Rayleigh limit (Stecher & Donn 1965; Lillie & Witt 1976; Morgan, Nandy, & Thompson 1976; Mathis 1994). However, in specific environments or under specific physical and geometrical conditions, part of the bump may be due to enhanced scattering around 2200 Å.

Evidence of enhanced scattering in the bump was reported for IC 435 and CED 201 by Witt, Bohlin, & Stecher (1986a). In the case of IC 435, the enhanced scattering, the low far-UV extinction curve toward the illuminating star HD 38087 (Witt, Bohlin, & Stecher 1984), and the displacement of the 2175 Å bump to a peak wavelength of 2193 Å (Fitzpatrick & Massa 1986) suggest depletion of small grains, which is typical of dense regions (Witt et al. 1984). Finally, the bump seen toward HD 38087 is unusually strong compared to the average interstellar medium.

We report the results from recent, high signal-to-noise ratio (S/N) *IUE* observations of two regions in IC 435 at different radial distances from the central illuminating star. Optical data on the nebula from Witt & Schild (1986) define a model for the dust density distribution in the nebula. The two UV spectra at different offsets allow us to calculate independently the albedo and the phase function asymmetry of the dust as functions of wavelength.

2. DATA

IC 435 ($\alpha[1950] = 05^h40^m29^s.5$, $\delta[1950] = -02°20'05''$) is a bright, symmetric reflection nebula, about 2'.5 in radius, situated at a distance of about 550 pc from the Sun in the northern Orion molecular cloud L1630 (Witt & Schild 1986). The nebula is illuminated by the B5 V star HD 38087 ($E[B-V] = 0.29$; see Guetter 1979; Schild & Chaffee 1971), which is located approximately in the center of the projected nebular region.

Two regions in the nebula, IC 435-1 and IC 435-2, were observed with *IUE*, at 23''.4 and 43''.3 northeast from the central illuminating star, yielding ~6 Å resolution spectra in the wavelength range 1200–3000 Å. The observations were obtained via service observing at both the NASA/GSFC and the ESA/VILSPA stations. The observational log is given in Table 1. The spectra for the two positions are reduced and co-added using the optimal extraction routine by Kinney, Bohlin, & Neill (1991). The nebular spectra are corrected for the instrumentally scattered stellar light (Witt et al. 1982): the contamination is ~10% for IC 435-1 and ~4% for IC 435-2.

A total of six short-wavelength and five long-wavelength UV spectra for HD 38087 were retrieved from the *IUE* archive,

TABLE 1

LOG OF THE *IUE* OBSERVATIONS

Name	Position	Image Number	Exposure (minutes)	Date
IC 435-1……	16″.2 E, 16″.9 N	SWP 52769	300	1994 Nov 9
		LWP 29481	337	1994 Nov 9
		LWP 29492	370	1994 Nov 11
IC 435-2……	30″.3 E, 31″.0 N	SWP 52781	320	1994 Nov 11
		LWP 29486	360	1994 Nov 10
		LWP 29557	407	1994 Nov 24

and they are calibrated and co-added using the same routine as for the nebular spectra. The ratio of the nebular surface brightness to the stellar flux, log (S/F_*), is shown in Figure 1 for the two nebular regions. The solid angle subtended by the *IUE* slit is 200 square arcsec or 4.8×10^{-9} sr.

One SWP and one LWR spectrum of a region in IC 435 $\sim 2''$ northeast of our IC 435-1 exist in the *IUE* archive (see Witt et al. 1986a, who report the position of the region to be in the northwest sector of the nebula, instead of the true position in the northeast sector). The total exposure time for IC 435-1 is about a factor 10 larger than the old spectrum in each of the two *IUE* cameras.

For the $10'' \times 20''$ *IUE* aperture, the IC 435-1 region and the archival region are nearly coincident and should have identical UV spectra. Differences in the aperture orientation of 189° for our images and 145° for the archival images (N = 0° and E = 90°) can cause different contamination of the nebular spectra from instrumentally scattered stellar light; however, this contamination is at the level of about 10% of the observed flux, and the uncertainty is $\leq 5\%$. The ratio of the nebular surface brightness to the stellar flux for the archival spectrum is reported also in Figure 1.

The LWR archival spectrum agrees with the LWP IC 435-1 spectrum within the uncertainties. The small excess in the 1994 spectrum longward of 2800 Å can be attributed to the recently developed problem of solar contamination in the LWP camera. On the other hand, the SWP archival spectrum is about a factor 2 below the IC 435-1 spectrum. As a net effect,

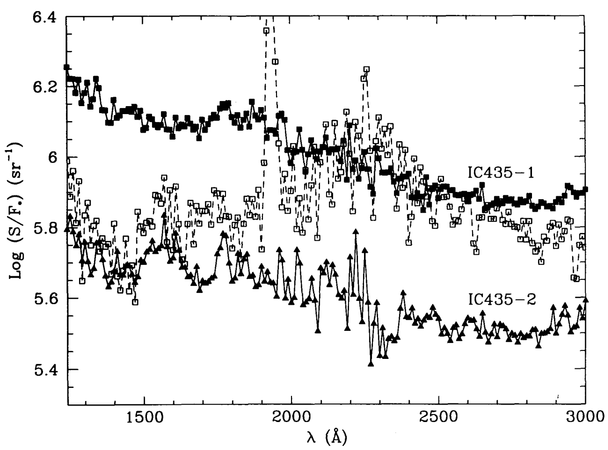

FIG. 1.—The ratio of the nebular intensity to the stellar flux, log (S/F_*), is shown for the two regions observed in IC 435, namely, IC 435-1 (*solid squares* and *solid line*) and IC 435-2 (*solid triangles* and *solid line*), and for the archival spectrum (*open squares* and *dashed line*). The spectra are binned over 10 Å. The coordinates of the archival spectrum coincide with IC 435-1, while the two spectra differ markedly at short wavelengths.

the (S/F_*) ratio of the archival nebular intensity to the stellar flux shows an excess around 2300 Å, which led Witt et al. (1986a) to conclude that there is enhanced scattering in the bump of the nebula. The reason for the strong difference between the archival and the new spectra is unclear. Some instrumental background problem, coupled with the low S/N of the old observations, may be at the origin of the low net SWP archival spectrum.

There is no evidence for enhanced scattering at the bump wavelengths in the (S/F_*) ratio of the new spectra (see Fig. 1).

Photometric data for IC 435 in the *B* and *V* bandpasses are from Witt & Schild (1986), who used a thinned CCD detector for their observations. The nebular surface brightness in the two filters was mapped by these authors at various distances and positions from HD 38087, using an aperture of 10″.24 in diameter. The *R* and *I* data of Witt & Schild (1986) were considered unsuitable for the present study because of the presence of extended red emission (ERE) in these bandpasses.

Detailed spatial information for the nebular surface brightness up to 140″ from the illuminating star allows us to model the nebular dust density distribution. In addition, two of the positions reported by Witt & Schild (1986) coincide with the positions of IC 435-1 and IC 435-2 and provide an extension of our UV spectra to optical wavelengths.

3. A MODEL OF IC 435

Derivations of dust scattering properties from reflection nebula observations are strongly model dependent. Usually, such exercises are only meaningful when observations covering a range of wavelengths are available, and the aim is to derive the *relative* variation of scattering properties with wavelength for a constant geometry. Information needed in this case includes the wavelength dependence of extinction by the nebular dust and an estimate of the dust fraction which is involved in the nebula, usually less than the total column density of dust between the illuminating star and the observer. Extensive surface brightness measurements at *one* wavelength are helpful in constraining the details of the nebular geometry. All these conditions are satisfied in the case of IC 435.

The wavelength dependence of the extinction toward HD 38087 (Witt et al. 1984) is characterized by a far-UV rise lower than the average, which is typical of dense regions with larger than average dust grains (Cardelli, Clayton, & Mathis 1989; Snow & Witt 1989). Dense regions are also characterized by large values of the total-to-selective extinction $R_V = A(V)/E(B-V)$, and we use the value $R_V = 5.3$ from Cardelli et al. (1989) to extend the UV values of the HD 38087 extinction curve toward optical wavelengths. The results are shown in Figure 2: the HD 38087 extinction curve is fairly well reproduced by the Cardelli et al. (1989) curve for $R_V = 5.3$, except for the unusually strong 2175 Å feature.

The nebular spectra of IC 435-1 and IC 435-2 exhibit strong depressions due to the 2175 Å band, which are both similar to that in the illuminating star and indicate that most of the dust toward HD 38087 is located at distances from the star greater than the 0.4 pc radius of the nebula. The scattering in IC 435 must be dominated by single scattering, which is consistent with a fairly small radial optical depth. If more of the extinction were to occur within IC 435 itself, a *greater* 2175 Å band strength should appear in the spectrum with the *larger* offset, which is *not* the case. Thus, the column density of dust associated with IC 435 itself is estimated as $E(B-V) = 0.06$ or $\tau_V = 0.29$, which is only $\sim 20\%$ of the total observed extinction. As

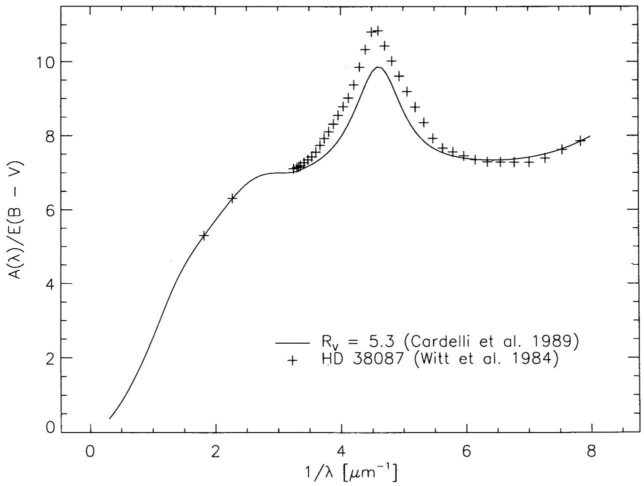

FIG. 2.—The extinction $A(\lambda)/E(B-V)$ toward HD 38087 (*crosses*) is shown in comparison to the standard extinction curve of Cardelli et al. (1989) for $R_V = 5.3$ (*solid line*).

will be shown in the next section, this value of the optical depth, when combined with the geometrical model and the extensive surface brightness measurements of IC 435 in the *B* and *V* bands, yields results for the dust albedo and the phase function asymmetry at *B* and *V* which are consistent with results obtained from numerous other studies of interstellar scattering (Gordon et al. 1994 and references therein).

The geometrical distribution of dust with $\tau_V = 0.29$ in front of HD 38087 is derived by modeling the detailed surface brightness distribution in the *B* band using a Monte Carlo code (Witt 1977; Witt et al. 1982, 1992; Gordon et al. 1994). The radial density profile for the dust is characterized by a shell-like structure. A low-density region of radius about 0.16 pc surrounds the central star, from 0.16 pc to 0.3 pc the density increases up to about 2.7 times the central value, and a steady decrease in density down to zero follows out to 0.4 pc. This density distribution is very close to that derived for IC 435 by Witt & Sturm (1990). A fit of this spherically symmetric model to the *B*-band data of Witt & Schild (1986) is shown in Figure 3, using the distance of 550 pc to IC 435.

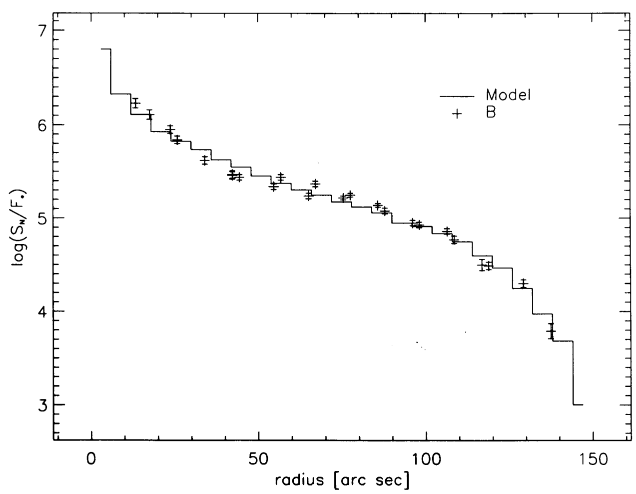

FIG. 3.—The observed ratio of the nebular intensity to the stellar flux, log (S_N/F_*), in the *B*-band (*crosses*) is plotted as a function of the projected distance from HD 38087. The fit to the data from the geometrical model for the dust density distribution discussed in § 3 is also shown (*solid line*).

For the derivation of UV scattering properties, we apply the same geometrical model to the *IUE* observations at the two offset distances, varying only the optical depth according to the extinction law given in Figure 2.

4. RESULTS

The separate fits to the surface brightness spectra of IC 435-1 and IC 435-2, at 50 Å intervals, yield formally independent solutions for both the albedo and the phase function asymmetry, with mutually dependent uncertainties. The results are shown in Figure 4.

The most important findings are a broad minimum in the albedo associated with the 2175 Å band, followed by rising albedo values in the far-UV. The minimum for the albedo, $a \simeq 0.4$, is reached at $\lambda \simeq 2300$ Å. Below 1600 Å, the albedo has values around 0.7–0.8, which is higher by about 40% than the corresponding values in the *B* and *V* bands, $a_B = 0.63$ and $a_V = 0.48$. The solutions for the phase function asymmetry, *g*, are indicative of a constant value of $g \approx 0.6$ from 5500 to 3000 Å, with a subsequent rise to $g = 0.75 \pm 0.05$ near 1500 Å. The scatter in the values of *g* and *a* is due to the independent noise in the original data at the two offset positions, which may result in a lower formal solution for *a*, compensated for by a higher *g*-value, or vice-versa.

Since $a = Q_{sca}/Q_{ext}$ and $Q_{abs} = Q_{ext} - Q_{sca}$, the wavelength-dependent values of *a* and of the extinction efficiency $Q_{ext} \propto A_\lambda/E_{B-V}$ (see Figure 2) are used to derive the scattering efficiency Q_{sca} and the absorption efficiency Q_{abs} for the nebular dust. The results are shown in Figure 5; the 2175 Å bump in the extinction curve of HD 38087 is entirely due to absorption, while the scattering efficiency exhibits a gradual increase toward the UV.

5. DISCUSSION AND CONCLUSIONS

Our results show a steadily increasing phase function asymmetry and mirror the findings of Witt et al. (1992) for the bright reflection NGC 7023. The trend toward larger *g*-values appears stronger in IC 435 and may be explained by the larger than average size of the dust grains toward HD 38087, as

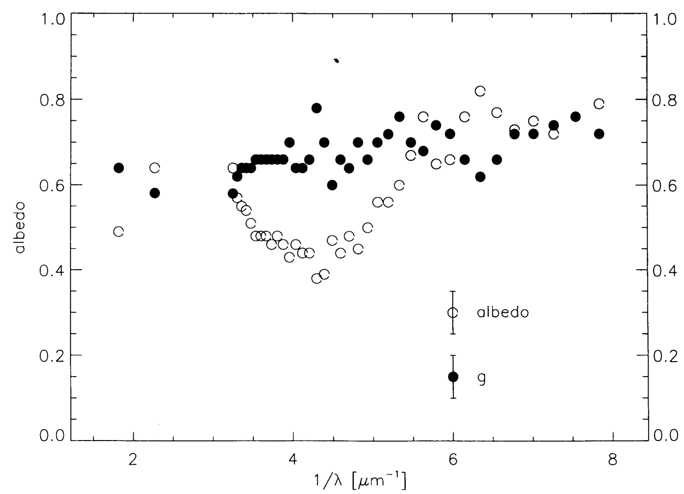

FIG. 4.—The albedo *a* and phase function asymmetry *g* are shown as a function of λ^{-1}. The UV values are derived from the *IUE* spectra of the two offset position in the nebula, IC 435-1 and IC 435-2. The values at *B* ($\lambda = 4400$ Å) and *V* ($\lambda = 5500$ Å) are derived from the nebular data of Witt & Schild (1986) at the same offset positions of the *IUE* spectra. Typical 1 σ error bars for *a* and *g* are also shown.

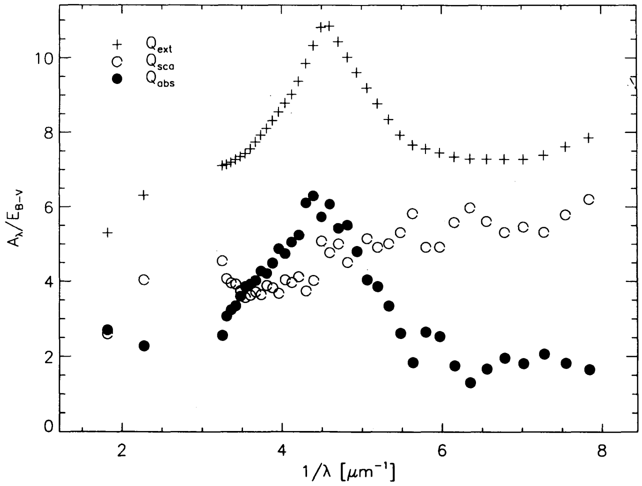

FIG. 5.—The scattering (*open circles*) and absorption (*filled circles*) components, Q_{sca} and Q_{abs}, respectively, of the extinction efficiency are shown. The dust extinction efficiency, Q_{ext}, is proportional to the extinction curve for HD 38087 (*plus signs*).

discussed by Snow & Witt (1989). The albedo values at the shortest UV wavelengths are higher than found in any previous investigation (e.g., Gordon et al. 1994). However, such results were anticipated by Witt et al. (1993), who associated the decline of the dust albedo found in NGC 7023 at wavelengths shorter than 1300 Å with the presence of a steeply rising extinction curve, caused by small absorbing grains. HD 38087 exhibits an unusually flat extinction curve in the UV (Witt et al. 1984; see Fig. 2) with little sign of the presence of small grain absorption. For such cases, Witt et al. (1993) had predicted a high far-UV albedo.

The albedo minimum centered near 2300 Å is very similar in width and depth to the albedo minimum found from the study of the diffuse galactic light by Lillie & Witt (1976). These results are also consistent with the *IUE* spectra of the Pleiades reflection nebulae (Witt, Bohlin, & Stecher 1986b), which indicated a higher albedo at wavelengths shortward of 2000 Å compared to the 2200–2700 Å range.

Our values for the albedo and phase function asymmetry are in remarkable agreement with the predictions of the "modified astronomical silicate" model with $R_V = 5.3$ by Kim & Martin (1995). There are, however, two noticeable differences: the albedo minimum is broader and deeper in our data than in their model, and we do not see the decline in the albedo values for $\lambda^{-1} > 6$ μm. Both differences can be attributed to the peculiarities of the extinction curve toward IC 435 compared to the "standard" interstellar extinction curve (see § 3; cf. Witt et al. 1993).

The present results have implications for the interpretation of the dust obscuration curve in external starburst galaxies (Calzetti et al. 1994). In agreement with studies on other reflection nebulae (Gordon et al. 1994), the 2175 Å bump in the interstellar extinction curve toward HD 38087 is confirmed as entirely due to absorption by dust grains. Therefore, the absence of the bump in the obscuration curve of starburst galaxies is difficult to explain in terms of geometrical effects alone, even if complex models are used for the distribution of stars and dust. Indeed, the lack of the bump is observationally coupled with reddened UV spectra. Geometrical models which can lower the importance of the 2175 Å feature tend also to predict rather blue UV spectra. The presence of enhanced scattering in the bump would have helped the geometrical interpretation, since, under specific conditions, a fraction of the bump strength would have been associated with excess scattering. However, the presence of enhanced scattering in the bump, suggested by previous observations, is not confirmed in IC 435.

The authors thank the *IUE* Observatory staff at NASA/GSFC and at ESA/VILSPA (in particular, VILSPA resident astronomer C. La Dous and GSFC resident astronomers L. Rawley and T. Teasy) for carrying out the observations through Service Observing. D. C. acknowledges support from the NASA grant NAGW-3757 during this research. K. D. G. and A. N. W. acknowledge the support from NASA LTSAP grant NAGW-3168.

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