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Interstellar Dust Scattering Properties

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Abstract. Studies of dust scattering properties in astrophysical objects with Milky Way interstellar dust are reviewed. Such objects are reflection nebulae, dark clouds, and the Diffuse Galactic Light (DGL). To ensure their basic quality, studies had to satisfy four basic criteria to be included in this review. These four criteria significantly reduced the scatter in dust properties measurements, especially in the case of the DGL. Determinations of dust scattering properties were found to be internally consistent for each object type as well as consistent between object types. The 2175 Å bump is seen as an absorption feature. Comparisons with dust grain models find general agreement with significant disagreements at particular wavelengths (especially in the far-ultraviolet). Finally, unanswered questions and future directions are enumerated.

1. Introduction

The scattering properties of dust provide a unique view into the physical properties of dust grains. This view is different from other probes of dust grains (eg., extinction, polarization due to differential extinction, abundances) as it allows their absorption and scattering properties to be separated. The scattering properties of dust grains are indicators of the size and composition of dust grains.

The scattering of photons by dust grains can be described by a single scattering albedo, a, and a scattering phase function, $\Phi(\alpha)$, where α is the scattering angle. In most studies, $\Phi(\alpha)$ is approximated by the single parameter Henyey-Green (1941) phase function

$$\Phi_{HG}(\alpha) = \frac{(1-g^2)}{4\pi\left(1+g^2+2g\cos\alpha\right)^{3/2}} \tag{1}$$

where

$$g = \int \Phi(\alpha)\cos\alpha \; d\Omega = \langle\cos\alpha\rangle \, . \tag{2}$$

The g parameter is referred to as the scattering phase function asymmetry and varies from -1 (complete back scattering) to 0 (isotropic scattering) to 1 (complete forward scattering). This Henyey-Greenstein phase function is a good approximation for dust grains, except possible in the far-ultraviolet (Witt 1989). Other analytic forms of the scattering phase function have been proposed (e.g., Cornette & Shanks 1992; Draine 2003b), but have yet to be used in dust scattering studies.

There are three astrophysical objects which are suited for studies of Milky Way interstellar dust scattering properties. These are reflection nebulae, dark clouds, and the Diffuse Galactic Light (DGL). These objects consist of either high-density or diffuse dust illuminated by sufficiently strong sources to permit the detection of scattered light. Reflection nebulae usually consist of a single or small number of stars illuminating their natal cloud. Dark clouds are isolated dust clouds which are usually illuminated by the interstellar radiation field. The DGL is the sum of the light of the stars in the Milky Way scattered by dust in the Galaxy. Other objects which do show scattering light, but which are not suitable for such studies are circumstellar disks, H II regions, and external galaxies. These objects have dust which is newly formed, processed, or non-Milky Way dust.

Each of these three astrophysical objects have different strengths and weaknesses with respect to determining dust scattering properties. The strengths of reflection nebulae are that they are bright, have simple, wavelength independent illuminator geometries, and are illuminated by a single or handful of stars. Their weaknesses are that they often have strong emissions in the red (Extended Red Emission [ERE]) and near-infrared (non-equilibrium, thermal small particle emission). In addition, they usually probe high density regions ($R_V > 3.1$) making the results harder to compare to most dust grain models. The strengths of dark clouds are that they have simple, wavelength independent illuminator geometries and are externally illuminated by the interstellar radiation field and/or a small number of stars. Dark clouds share the same weakness as reflection nebulae as they also probe high density regions ($R_V > 3.1$) and, in addition, they are difficult to observe as they are faint. The strength of the DGL is that it probes the diffuse interstellar medium ($R_V = 3.1$). The weaknesses of the DGL are that the illuminator geometry is wavelength dependent and the dust geometry is complex having a disk density distribution with embedded dust clouds. In addition, DGL observations are challenging as observations of the faint DGL signal are needed over a fairly large region of the sky, especially a range of galactic latitudes, to allow for accurate measurements of a and g. The combination of the results from all three astrophysical objects should give a good view of dust scattering properties without undue uncertainties resulting from each object type's weaknesses.

This review will concentrate on published studies of interstellar dust scattering properties in the ultraviolet, visible, and near-infrared. The topic of X-ray scattering by dust is covered elsewhere in these proceedings. A great deal of work has taken place in this area since the review of dust scattering properties at the last dust meeting (Witt 1989). At that time, only a handful of studies existed which made quantitative determinations of dust scattering properties (ie., actually determined values for a and g). Since the last dust meeting, a number of studies have specifically been addressed to this issue.

Brief summaries of these studies, usually in the form of plots of a and g as a function of wavelength, have been presented in the literature (eg., Gordon et al. 1994; Mathis 1996; Li & Greenberg 1997; Witt & Gordon 2000; Draine 2003a, 2003b). One drawback to these reviews has been the inclusion of all literature results without consideration of the quality of each study. This has lead to a misplaced notion that our knowledge of dust scattering properties is quite uncertain in some wavelength regions. This has been especially pronounced in studies of the DGL in the far-ultraviolet (around 1500 Å). In a handful of these studies, preliminary analyses have been revised in later papers resulting in significantly higher determinations of both a and g. Thus, it is important to apply a uniform set of criteria when reviewing dust scattering studies to ensure the basic quality of the results. This has been done in this review.

2. Literature Results

The literature was searched for determinations of dust scattering properties in objects possessing Milky Way interstellar dust. Astrophysical objects which satisfy this constraint are reflection nebulae, dark clouds, and the DGL.

For inclusion in this review, each study had to satisfy four criteria. These criteria are:

1. *Determine albedo & g*: This requires that specific values be quoted for the two quantities. Studies which were only sensitive to one of the two quantities were included as long as a realistic range of the other quantity was probed. Usually, the albedo (a) was the quantity determined with calculations performed for g values between zero and one. While this criteria means that the large number of early studies which only put limits on a and/or g are neglected, their limits are usually consistent with the values determined from later studies.

2. *Determine uncertainties*: The importance of this criteria cannot be understated. The uncertainties presented here are either the uncertainties quoted in the original paper or reflect the range of a & g values allowed by models presented in each study. This can mean that multiple models (with different assumptions) have been combined into a single measurement with larger uncertainties than a single model.

3. *Refereed Publication*: This ensures that the full details of the work have be presented. In addition to the usual journals (eg., ApJ, AJ, A&A, PASP, MNRAS, etc.), theses were counted as refereed publications.

4. *Not be superseded by other work*: A number of studies are superseded by newer work which usually used better radiative transfer models (especially the case for DGL studies). This usually results in significantly different determinations of a & g.

The studies satisfying the first three criteria are listed in Table 1, separated by astrophysical object studied. These tables give the study reference, a brief description, a model code, and whether the study satisfied the fourth criteria and, as such, was included in Figs. 1-4. Each model code is explained in Table 2 where the method of calculation, sources, and dust geometry are summarized. Ideally, the model used to interpret the observations of a specific object would include realistic illuminators (location and spectrum), a realistic dust distribution, and calculate the full multiple scattering of photons. This ideal is unlikely to be fully met by any specific model, but models which come closest have the best chance of producing good dust scattering properties. The original study reference should be consulted for the full details of each study.

The a and g values for the studies which satisfy all four criteria are plotted separate in Figs. 1-3 for reflection nebulae, dark clouds, and the DGL. In addition, predictions for different dust grain models are included in these figures (see §3.1. for model details). The results have been divided between object classes to highlight their differences. It would not be surprising to find real differences in the a and g values between object classes. For example, reflection nebulae and dark clouds possess, on average, larger dust grains than the DGL. This is seen from the different R_V values measured for these objects as R_V is a rough measure of the average grain size. Examining the results separately also allows for the impact of the different strengths and weaknesses of each object on the derived scattering parameters to be examined. The final reason to separate the results is to check if the assumptions in the modeling based on object type significantly affect the resulting scattering values. All of the a and g values have been plotted together in Fig. 4 to check the consistency of determinations between the three astrophysical object types.

3. Discussion

The brightness and relative compactness of reflection nebulae have led to determinations of dust scattering properties with a finer wavelength sampling and smaller uncertainties than in either dark clouds or the DGL (see Fig. 1). Due to the usual presence of strong emissions (ERE and non-equilibrium emission), reflection nebulae have only provided scattering information in the ultraviolet and blue-optical. While dark clouds are faint, their relative compactness and usual lack of strong emissions has made them valuable as probes of dust scattering properties in the red-optical and near-infrared (Fig. 2). The one drawback to both reflection nebulae and dark cloud studies is that they probe higher density media than diffuse interstellar medium. This leads to questions to the general applicability of reflection nebulae and dark clouds results.

The faintness and large extent of the DGL makes it the most challenging object to both observe and model. The importance of measuring dust scattering properties in the diffuse interstellar medium and determinations of the extragalactic background has resulted in considerable effort being expended on the study of the DGL. Determinations of DGL dust scattering properties in the blue-optical and near-ultraviolet have been fairly uncontroversial, while such determinations in the far-ultraviolet have been quite controversial. This controversy is highlighted by the back-to-back reviews on the ultraviolet background in which it was argued that the majority of the ultraviolet background is from dust scattered light (Bowyer 1991) or extragalactic light (Henry 1991). The difficulties in both observing and modeling the DGL in the far-ultraviolet has led to studies in the literature with conflicting results, either low a and g values or high a and g values. This is the area which was most affected by the fourth criteria (not superseded by a more recent study). A number of initial analyses giving low a and g values were superseded by subsequent studies using more sophisticated models which found higher a and g values. As a result, the scatter

Table 1. Literature Dust Scattering Studies

Reference	Description	Model	Inc.
	Reflection Nebulae		
Witt et al. 1982	NGC 7023; IUE 1200–3000 Å & ground-based 3470–5515 Å	RN1	Yes[1]
Witt et al. 1992	NGC 7023; UIT 1400 & 2800 Å	RN1	Yes
Witt et al. 1993	NGC 7023; Vogager 2 1000–1300 Å	RN1	Yes
Gordon et al. 1994	Sco OB2; 1365 & 1769 Å	RN2	Yes
Calzetti et al. 1995	IC 435; IUE 1200–3100 Å & ground-based B & V	RN1	Yes
Burgh et al. 2002	NGC 2023; FOT 900–1400 Å	RN1	Yes
Gibson et al. 2003	Pleiades; WISP 1650 & 2200 Å	RN3	Yes
	Dark Clouds		
Matilla 1970	Coalsack and Libra dark cloud; UBV	DC1	Yes
Fitzgerald et al. 1976	Thumbprint Nebula; B	DC1	Yes
Laureijs et al. 1987	L1642; 3500–5500 Å	DC1	Yes[2]
Witt et al. 1990	Bok globule; 4690–8560 Å	DC1	Yes
Hurwitz 1994	Taurus molecular cloud; Berkeley UVX 1600 Å	DC2	Yes
Haikala et al. 1995	G251.2+73.3 cirrus cloud; FAUST 1400–1800 Å	DC1	Yes
Lehtinen & Mattila 1996	Thumbprint Nebula; JHK	DC1	Yes[2]
	Diffuse Galactic Light		
Witt 1968	ground-based 3600, 4350, & 6100 Å	DGL1	No[3]
Mathis 1973	ground-based 3600 & 4350 Å	DGL2	Yes[2]
Witt & Lillie 1973	OAO-2 1500–4200 Å	DGL3	No[4]
Lillie & Witt 1976	OAO-2 1500–4200 Å	DGL2	Yes
Morgan et al. 1976	TD-1 2350 & 2740 Å	DGL3	Yes[2]
Toller 1981	Pioneer 10 4400 Å	DGL4	Yes
Hurwitz et al. 1991	Berkeley UVX 1625 Å	DGL5	No[5]
Murthy et al. 1993	Voyager 2 1050 Å	DGL6	Yes[2]
Murthy & Henry 1995	Berkley UVX & others	DGL6	Yes[2]
Sasseen & Deharveng 1996	FAUST 1565 Å	DGL7	No[6]
Petersohn 1997	DE 1 1565 Å	DGL8	Yes
Witt et al. 1997	FAUST 1564 Å	DGL8	Yes
Schiminovich et al. 2001	NUVIEWS 1740 Å	DGL9	Yes

[1]UV g determinations not included, not enough radial data for unique g solution
[2]No g determination possible
[3]Superseded by Mathis 1973
[4]Superseded by Lillie & Witt 1976
[5]Superseded by Murthy & Henry 1995
[6]Superseded by Witt et al. 1997

Table 2. Radiative Transfer Models

Name	Method	Sources	Dust Geometry
RN1	Monte Carlo	single star	homogeneous sphere
RN2	Monte Carlo	multiple stars	homogeneous sphere
RN3	analytic single scattering	multiple stars	approximated clumpy slab
DC1	Monte Carlo	MW ISRF & specific stars	homogeneous sphere
DC2	numerical int.	MW ISRF	2D distribution
DGL1	analytic	Galaxy model	homogeneous slab
DGL2	numerical int. n=8 scatterings	MW ISRF boundary condition	infinite cylinder
DGL3	analytic	constant	infinite slab
DGL4	numerical int. n=2 scatterings	star counts	non-homogeneous
DGL5	numerical int.	TD-1 star catalog	clumped dust
DGL6	numerical int.	SKYMAP catalog	dust based on HI survey
DGL7	Monte Carlo	star catalogs	dust based on HI survey
DGL8	Monte Carlo	TD-1 star catalog	dust cloud spectrum based on HI survey
DGL9	Monte Carlo	3D TD-1 star catalog	dust cloud spectrum based on HI survey

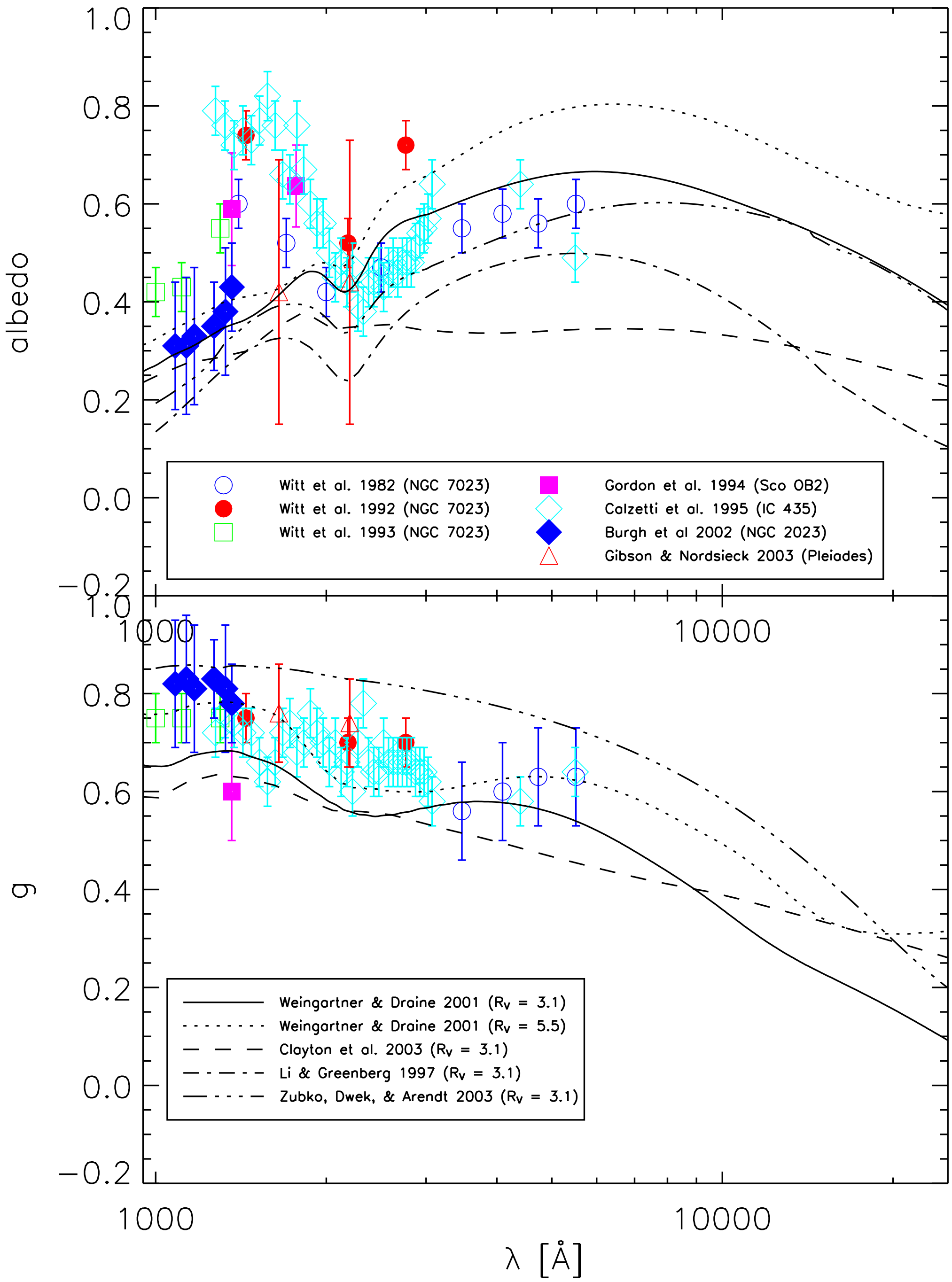

Figure 1. Determinations of the albedo and g in reflection nebulae are plotted versus wavelength. In addition, predictions from dust grain models are plotted for comparison.

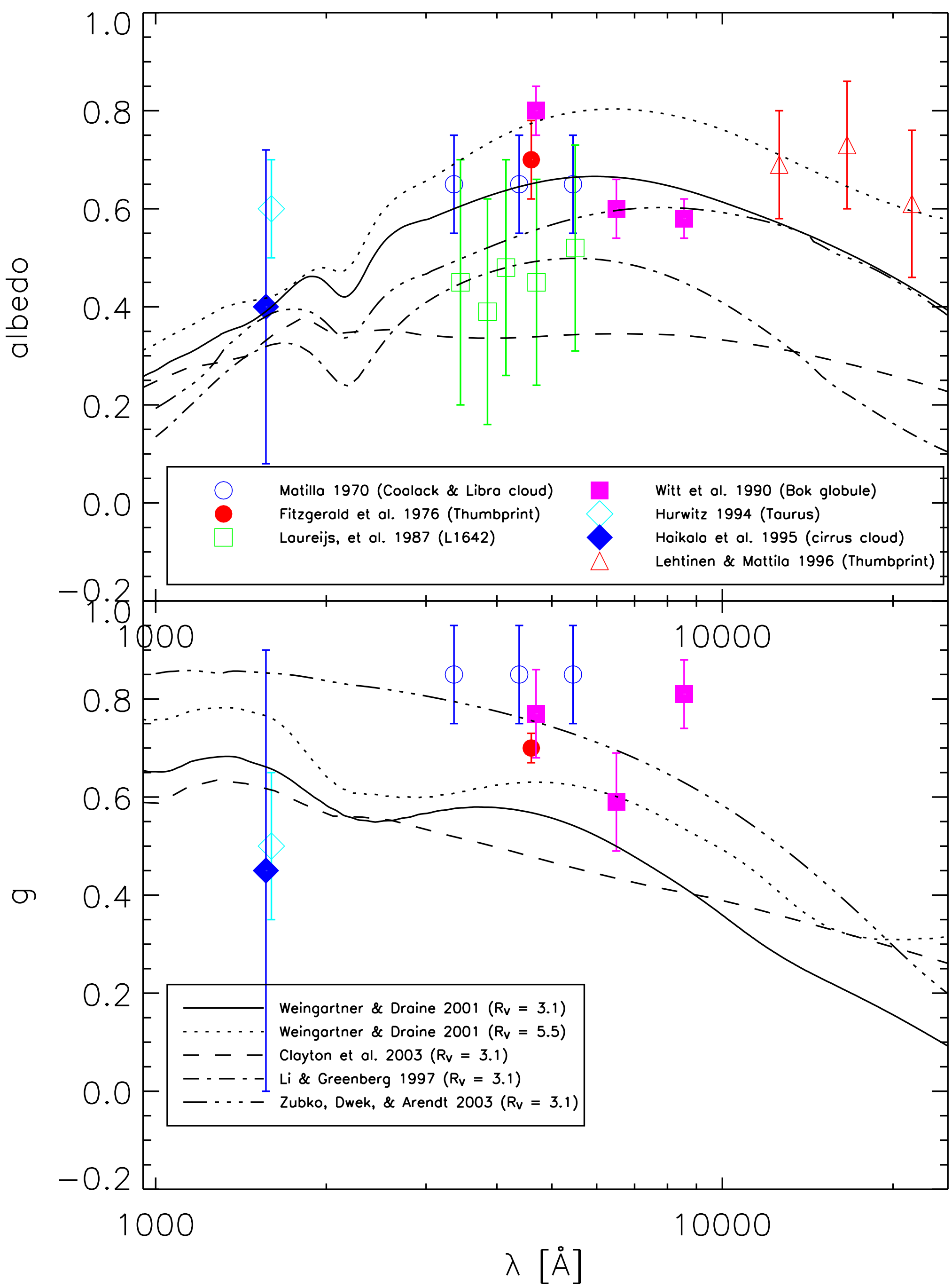

Figure 2. Determinations of the albedo and g in dark clouds are plotted versus wavelength. In addition, predictions from dust grain models are plotted for comparison.

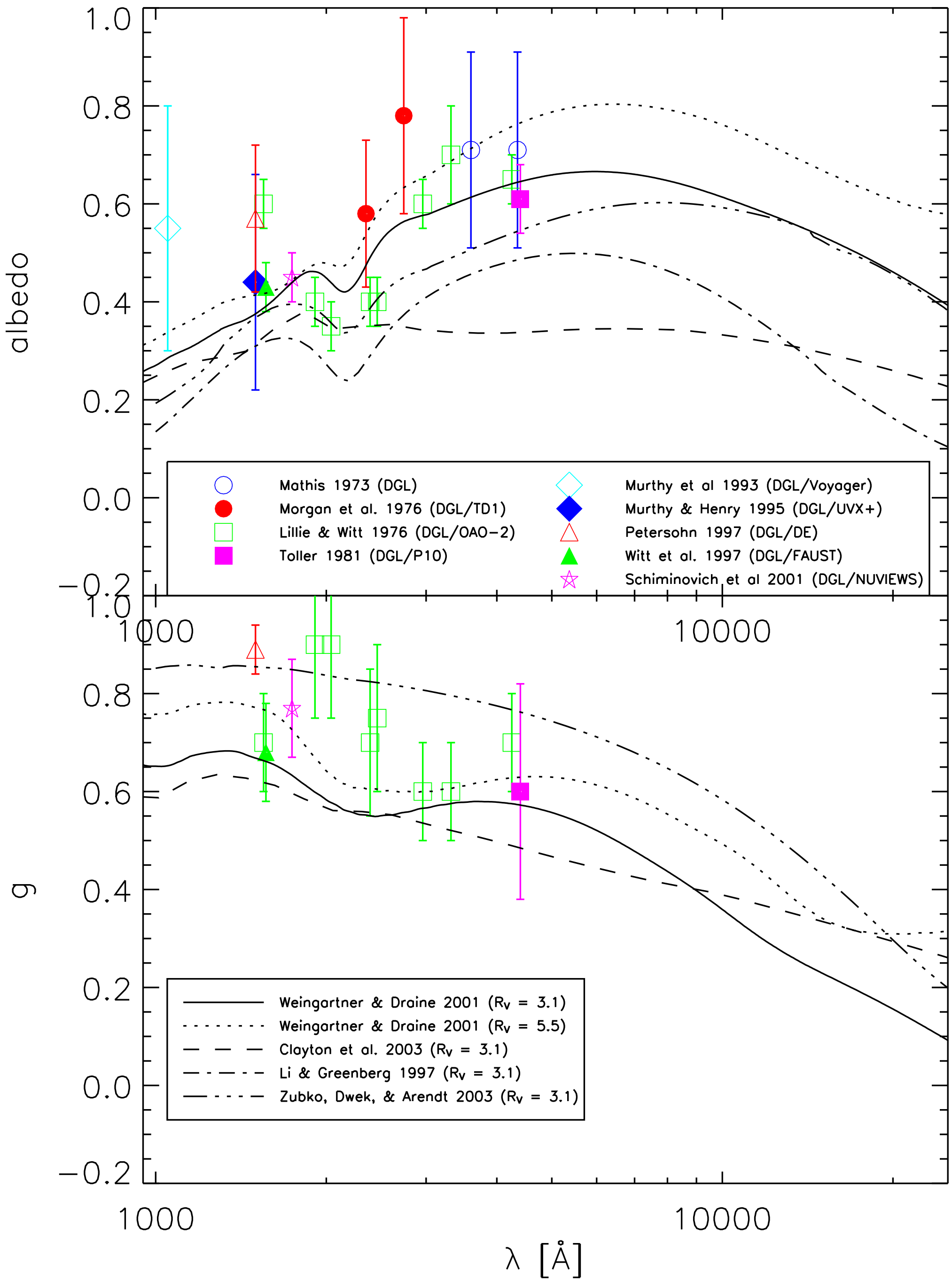

Figure 3. Determinations of the albedo and g in the DGL are plotted versus wavelength. In addition, predictions from dust grain models are plotted for comparison.

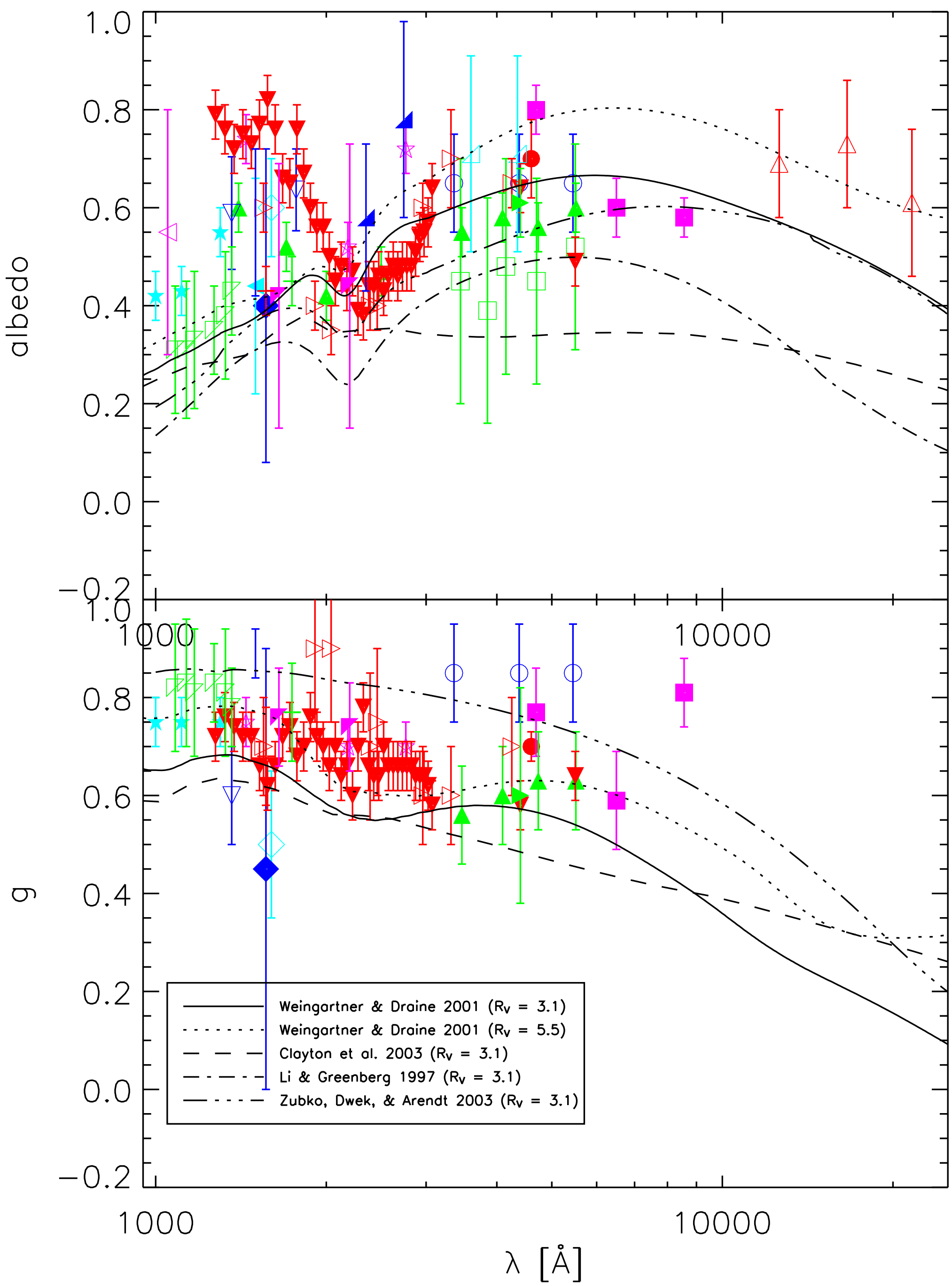

Figure 4. The combined determinations of the albedo and g in reflection nebulae, dark clouds, and the DGL are plotted versus wavelength. The plot symbols are not identified and do not correspond to legends in previous figures, see Figs. 1-3 for information about specific studies. In addition, predictions from dust grain models are plotted for comparison.

in the plots of a and g for the DGL (Fig. 3) is now within the quoted uncertainties. The values of a and g derived from DGL measurements are similar to those derived from reflection nebulae and dark clouds.

By examining Figs. 1-3, it can be seen that the a and g values derived for each object type are internally consistent. For example, the measurements of a and g from different reflection nebulae all are consistent with a single wavelength dependence. When examing these figures, it is important to remember that they include results from broad-band filters along with those derived from spectroscopy. Comparing the results for all three object types in Fig. 4, it can be seen that the same may be true in general and not just internal to an object type. The only area where the data from different object types may disagree is in the far-ultraviolet region for a measurements only. The uncertainties are large enough to make a strong statement either way difficult. The high level of agreement between object types implies that their different strengths and weaknesses as well as model assumptions are not severely biasing our view of dust scattering properties. This result goes a long way in answering the concerns raised by Mathis, Whitney, & Wood (2002) about possible biases in reflection nebulae measurements of the dust albedo caused by ignoring the known clumpiness of dust.

In fact, it is not unreasonable to say that the current data (see Fig. 4) indicates the wavelength dependence of the albedo is $\sim$0.6 in the near-infrared/optical with a dip to $\sim$0.4 for 2175 Å bump, a rise to $\sim$0.8 around 1500 Å, and a drop to $\sim$0.3 by 1000 Å. The wavelength dependence of g is simpler with a monotonic rise from 0.6 to 0.8 from 10000 to 1000 Å. The uncertainties do allow for significant real variation in the a and g values around these qualitative averages of at least 0.1.

The study of dust scattering properties has shed light on the nature of the 2175 Å bump and the far-ultraviolet rise features of extinction curves. Early work on the 2175 Å bump indicated that it was likely an absorption feature with no scattered component (eg., Lillie & Witt 1976). Subsequently, evidence for a scattered component in the 2175 Å bump was found in two reflection nebulae, CED 201 and IC 435, by Witt, Bohlin, & Stecher (1986). This results was found to definitely be spurious for IC 435 when much more sensitive observations were taken and analyzed by Calzetti et al. (1995). By inference, the observations of CED 201 are also likely to be spurious. As a result, all evidence currently supports a 2175 Å extinction bump which is only due to absorption. Similarly, examining the results of reflection nebulae (see Fig. 1) gives good evidence that a significant portion of the far-ultraviolet rise in extinction curves (1700 Å and shorter wavelengths) is due to absorption.

3.1. Comparisons with Dust Grain Models

One way to synthesize our knowledge of dust is to fit different observations of dust to a dust grain model. The main observational constraints for dust grain models are usually the diffuse ISM dust extinction curve and dust abundances (Weingartner & Draine 2001; Clayton et al. 2003). In addition, some dust grain models also fit the dust polarization (Kim & Martin 1994; Li & Greenberg 1997) and infrared emission spectrum (Zubko et al. 2003; Li & Draine 2001). Some dust grain models also have been fit to the denser dust extinction curves (Kim, Martin, & Hendry 1994; Weingartner & Draine 2001). No dust grain models have used the measured dust scattering properties as fitting constraints, but most do use the scattering properties as a consistency check.

In Figs. 1-4, predictions for a and g from recent dust grain models are plotted. The Zubko et al. (2003) model plotted is described as BARE-NC-B. All but one of the five model predictions plotted are for diffuse ISM dust ($R_V = 3.1$) and are then only directly comparable to the DGL dust scattering results. As can be seen from Fig. 3, the dust grain models are in fairly good agreement with the results for g, but most of the models underpredict a for most wavelengths. All the models have a small dip in a at the 2175 Å bump, but the dip is not as large as indicated by the DGL measurements. The models all predict lower far-ultraviolet albedos than have been measured in the DGL.

The one dust grain model for denser dust (Weingartner & Draine; $R_V = 5.5$) is directly comparable to the dust scattering measurements in reflection nebulae (Fig. 1) and dark clouds (Fig. 2) as these objects have similar R_V values. Similar to the DGL comparison, the g values predicted by the model are in reasonable agreement for reflection nebulae and dark clouds, except possible in the optical for dark clouds. The model predictions for a agree with the measurements for dark clouds which mainly probe the optical and near-infrared. The a predictions for reflection nebulae are generally too high in the optical and too low in the far-ultraviolet. The albedo dip at 2175 Å is much smaller in the model than the well measured values indicate. Basically, the recovery of the albedo at around 1500 Å is not seen in any of the dust grain models.

4. Summary and Future

This review of dust scattering determinations has concentrated on giving a critical examination of results presented in the literature for reflection nebulae, dark clouds, and the DGL. Unlike previous such reviews, each study was required to pass four simple criteria for inclusion in this review. There were a total of 23 studies passing the four criteria with 7 on reflection nebulae, 7 on dark clouds, and 9 on the DGL.

A great deal of progress has been made since the last review of this area (Witt 1989). The uncertainty in far-ultraviolet albedo from DGL studies has been resolved with the help of better observations and more sophisticated modeling. The 2175 Å bump has been shown to be an absorption feature; earlier indications of scattering in the bump have been traced to bad data. The measurements in reflection nebulae, dark clouds, and the DGL are roughly consistent alleviating earlier worries about the effects of the modeling assumptions specific to the object being studied (eg. reflection versus the DGL).

While much progress has been made in measuring dust scattering properties, there are a number of questions which are outstanding.

1. Does the assumption of the Henyey-Greenstein single parameter scattering phase function significantly bias the resulting dust scattering parameters (a and g)? This question is probably best answered with models of images of reflection nebulae and dark clouds which include either more complicated analytical phase functions (eg., a double Henyey-Greenstein phase

function; eq. 4 of Witt 1977) or scattering phase functions computed from dust grain models.

2. What are the a and g values in the near-infrared? Currently, there is only a measurements for a single dark cloud and no g measurements. The a and g values in the near-infrared probe the larger dust grains, information about which is difficult to determine from extinction curve measurements alone.

3. What are the a and g values in the red-optical and near-infrared for reflection nebulae? Is it even possible to determine a and g in reflection nebulae for these wavelengths? There are reflection nebulae in which ERE has not been detected (Witt & Boroson 1990). Are there nebulae without near-infrared, non-equilibrium emission?

4. Is it possible to measure dust scattering properties in the red-optical and near-infrared from DGL measurements?

5. What does it mean to measure dust scattering properties in objects without ERE or near-infrared, non-equilibrium emission if the diffuse ISM has been shown to have ERE (Gordon, Witt, & Friedmann 1998) and probably also has near-infrared, non-equilibrium emission.

6. Is it possible to use the full multiwavelength appearance of reflection nebulae and dark clouds to alleviate lingering concerns about the geometrical assumptions inherit in modeling such objects? Specifically, the inclusion of ultraviolet through far-infrared would provide direct measurements of the direct, scattered, and re-emitted light and thus require many fewer assumptions.

7. Is it feasible to consider using the full multiwavelength appearance of the DGL to reduce number of assumption necessary to model the DGL? Or is this still too complex of a problem, especially in light of the need for accurate 3D star positions of all stars important for the DGL (eg., hot stars in the ultraviolet and cooler stars at longer wavelengths)?

8. What are the real differences between dust scattering properties in reflection nebulae, dark clouds, and the DGL? The current evidence indicates they are consistent with each other at the $\sim$20% level.

9. Are the dust scattering properties in other galaxies different than those derived for Milky Way dust? The Large and Small Magellanic Clouds offer environments which have lower metallicities and high star formation rates than the Milky Way. In addition, dust extinction curves in the Magellanic Clouds have been measured to be quite different from Milky Way extinction curves (Gordon et al. 2003).

Finally, the author would like to encourage readers who find studies which have not been included in this review to email them to the author (currently kgordon@as.arizona.edu). The author is committed to continuing to update the web-based version of this review[1].

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