Light scattering by interstellar dust: Assessments of related direct and inverse problems

A. N. Witt*

Department of Physics & Astronomy, University of Toledo, Toledo, OH 43606, USA.

This summary provides a gateway to the literature on light scattering by interstellar dust.

INTRODUCTION

About half of the atoms heavier than helium in the interstellar medium (ISM) of the Milky Way Galaxy are in the form of interstellar dust, amounting to about 1% of the mass of the ISM. The most profound effect produced by interstellar dust is interstellar extinction of star light, resulting in an optical depth at visual wavelengths of about unity for a path length of about 3×10^{21} cm [1]. Consequently, with a diameter of the galactic disk near 1×10^{23} cm, the extinction by dust causes most parts of our Galaxy to be unobservable at optical wavelengths.

Interstellar extinction is caused both by absorption and scattering by solid grains exhibiting a wide size distribution ranging from a few 10^{-7} cm to a few 10^{-4} cm, with scattering by the larger grains being the dominant contribution to the extinction at most ultraviolet/visible/near-infrared wavelengths [2−4]. The study of the scattering properties of interstellar dust provides important constraints on the size distribution of the grains as well as critical information for astrophysical problems in which dust scattering is involved.

DIRECT PROBLEM: OPTICAL PROPERTIES OF SMALL PARTICLES

The early work by Mie [5] and the slow acceptance of the existence of interstellar dust by the astronomical community in the 1930's [1−4] allowed a rapid convergence of theory and observation [6,7], once the presence of dust particles in the diffuse interstellar medium of the Milky Way galaxy was established [8]. The monographs by van de Hulst [9] and Bohren & Huffman [10] provided the basis for the computation of the optical properties of interstellar grains, following Mie's [5] theory for homogeneous spherical particles. Although polarimetric observations have established the mostly non-spherical shape of interstellar grains, and although techniques for the computation of the optical properties of inhomogeneous, non-spherical particles have been developed (see Voshchinnikov [11] for a recent review), Mie's theory for spherical grains is still considered an adequate approximation for most applications, given the persistent uncertainties involving the chemical nature, physical structure, optical constants, and size distribution of interstellar dust [12]. These uncertainties will persist as long as remote sensing is the exclusive method for the study of the properties of interstellar grains. When needed, techniques such as the T-matrix method [13] or the discrete dipole approximation [14] are available for the computation of optical properties of

*Adolf N. Witt (Adolf.Witt@utoledo.edu)

non-spherical particles or particles of arbitrary shape and mixed composition, respectively. The most comprehensive resource on the theory of scattering by non-spherical particles currently available is the monograph by Borghese, Denti, and Saija [15]. Special computational tools have been developed for the determination of scattering properties of spherical particles with very large size parameters [16,17].

INDIRECT PROBLEM: SCATTERING PROPERTIES OF COSMIC DUST

Four classes of astrophysical systems exist in which scattering by interstellar grains can be observed and used as a basis for the empirical determination of their scattering properties. These are, in decreasing order of the angular extent, the sky as a whole, which contains the diffuse galactic light (DGL) produced by the general galactic dust distribution [18−20], illuminated by the interstellar radiation field (ISRF) due to all stars, followed by individual interstellar clouds illuminated externally [21] by the ISRF, then reflection nebulae [22−25], where individual clouds are illuminated by single or multiple embedded stars, and finally scattered light halos surrounding distant point sources, seen at both X-rays and optical light [26−28]. In all instances, appropriately designed radiative transfer models [17,22] are the essential tools that produce the link between observations and the scattering properties of the grains. The information typically derived are the dust albedo and the asymmetry of the scattering phase function as functions of wavelength, critical information about the sizes of grains, and finally information about the spatial distribution of the dust particles. The dust albedo, at most UV/visible/near-IR wavelengths, is $\sim 0.6 - 0.7$ and the phase function asymmetry parameter $g =< \cos\alpha >\sim 0.6 - 0.8$, indicating that interstellar scattering is dominated by highly reflective, strongly-forward scattering grains. The reduction of the dust albedo around the wavelength of the far-UV extinction feature at 2175 Å [25] shows that this feature is produced by absorbing nanoparticles. Similarly, the decline of the albedo at the shortest far-UV wavelengths [29] indicates the growing absorption contribution by the smallest interstellar grains. High-albedo scattering at near-IR wavelengths identifies astronomical environments where micron-sized grains dominate the scattering [30,31].

ASTRONOMICAL APPLICATIONS

The empirically determined scattering properties of interstellar dust are commonly used to constrain models of interstellar grains [32,33]. They also are critical input parameters for models designed to compute the dust attenuation in externally observed dusty galaxies, in which the dust-scattered radiation becomes a significant part of the total spectral energy distribution seen by a distant observer [34]. Finally, in addition to scattering, interstellar dust exhibits optical photoluminescence when exposed to ultraviolet observation. Knowledge of the wavelength dependence of the scattering properties is essential in order to separate the photoluminescence component from the scattered light component [35,36].

REFERENCES

[1] R.J. Trumpler. Spectrophotometric Measures of Interstellar Light Absorption. P. A. S. P. **42** (1930).

[2] O. Struve. On the Interpretation of the Surface Brightness of Diffuse Galactic Nebulae. ApJ **85** (1937).

[3] J.L. Greenstein and L.G. Henyey. The Ratio of Interstellar Absorption to Reddening. ApJ **93** (1941).

[4] L.G. Henyey and J.L. Greenstein. Diffuse Radiation in the Galaxy. ApJ **93** (1941).

[5] G. Mie. Beitraege zur Optik trueber Medien, speciell kolloidaler Metalloesungen. Ann. Phys. **25** (1908).

[6] C. Schalen. Untersuchungen ueber Dunkelnebel. Medd. Astron. Observ. Upsala **58** (1933).

[7] C. Schalen. Ueber Probleme der Interstellaren Absorption. Medd. Astron. Observ. Upsala **64** (1936).

[8] J.H. Oort and H.C. van de Hulst. Gas and Smoke in Interstellar Space. B. A. N. **10** (1946).

[9] H.C. van de Hulst. *Light Scattering by Small Particles*. New York: John Wiley & Sons, Publ. (1957).

[10] C.F. Bohren and D.R. Huffman. *Absorption and Scattering of Light by Small Particles*. New York: John Wiley & Sons, Publ. (1983).

[11] N.V. Voshchinnikov. Optics of Cosmic Dust I. Astroph. Space Phys. Rev. **12** Part 3 (2004).

[12] J.S. Mathis, W. Rumpl, and K.H. Nordsieck. The Size Distribution of Interstellar Grains. ApJ **217** (1977).

[13] H.K. Das, N.V. Voshchinnikov, and V.B. Il'in. Interstellar Extinction and Polarization — A Spheroidal Dust Grain Approach Perspective. MNRAS (in press) (2010).

[14] B.T. Draine and P.J. Flatau. Users Guide for the Discrete Dipole Approximation Code DDSCAT 7.1. http://arxiv.org/abs/1002.1505 (2010).

[15] F. Borghese, P. Denti, and R. Saija. *Scattering from Model Nonspherical Particles*. Berlin: Springer (2007).

[16] W.J. Wiscombe. Mie Scattering Calculations: Advances in Technique and Fast Vector-Speed Computer Codes. NCAR Tech. Note TN-140+STR, Boulder, NCAR (1979).

[17] S. Wolf and N.V. Voshchinnikov. Mie Scattering by Ensembles of Particles with very large Size Parameters. CmpPhC **162** (2004).

[18] P.A. Bastiaansen and H.C. van de Hulst. Models for Interpreting the Diffuse Galactic Light. A&A **61** (1977).

[19] J.S. Mathis. The Interpretation of the Diffuse Galactic Light. ApJ **186** (1973).

[20] A.N. Witt, B.C. Friedmann, and T.P. Sasseen. Radiative Transfer Analysis of Far-Ultraviolet Background Observations obtained with the Far Ultaviolet Space Telescope. ApJ **481** (1997).

[21] A.N. Witt, M.V. Oliveri, and R.E. Schild. The Scattering Properties and Density Distribution of Dust in a Small Interstellar Cloud. AJ **99** (1990).

[22] W. Rush. Albedo of Particles in Reflection Nebulae. AJ **80** (1975).

[23] J.S. Mathis, B.A. Whitney, and K. Wood. Can Reflection from Grains Diagnose the Albedo? ApJ **574** (2002).

[24] A.N. Witt et al. Ultraviolet Imaging Telescope Images of the Reflection Nebula NGC 7023: Derivation of Ultraviolet Scattering Properties of Dust Grains. ApJ **395** L5 (1992).

[25] D. Calzetti, R.C. Bohlin, K.D. Gordon, A.N. Witt, and L. Bianchi. Scattering Properties of the Dust in the Reflection Nebula IC 435. ApJ **446** L97 (1995).

[26] A.N. Witt, R.K. Smith, and E. Dwek. X-Ray Halos and Large Grains in the Diffuse Interstellar Medium. ApJ **550** L201 (2001).

[27] A. Socrates and B.T. Draine. Brilliant Pebbles: A Method for Detection of Very Large Interstellar Grains. ApJ **702** L77 (2009).

[28] N.J. Turner, K. Grogan, and J.B. Breckinridge. Probing Interstellar Dust with Space-Based Coronographs. ApJS **177** (2008).

[29] A.N. Witt et al. Voyager 2 Observations of NGC 7023: Dust Scattering Shortward of 1600 A. ApJ **410** (1993).

[30] A.N. Witt, R.S. Lindell, D.L. Block, and Rh. Evans. K'-Band Observations of the Evil Eye Galaxy: Are the Optical and Near-Infrared Albedos Identical? ApJ **427** (1994).

[31] J. Steinacker, L. Pagani, A. Bacmann, and S. Guieu. Direct Evidence of Dust Growth in L183 from MIR Light Scattering. arxiv0912.0145 (2009).

[32] B.T. Draine. Scattering by Interstellar Grains. I. Optical and Ultraviolet. ApJ **598** (2003).

[33] B.T. Draine. Scattering by Interstellar Grains. II. X-Rays. ApJ **598** (2003).

[34] D. Pierini, K.D. Gordon, A.N. Witt, and G.J. Madsen. Dust Attenuation in Late-Type Galaxies. I. Effects on Bulge and Disk Components. ApJ **617** (2004).

[35] A.N. Witt and T.A. Boroson. Spectroscopy of Extended Red Emission in Reflection Nebulae. ApJ **355** (1990).

[36] A.N. Witt, S. Mandel, P.H. Sell, T. Dixon, and U.P. Vijh. Extended Red Emission in High Galactic Latitude interstellar Clouds. ApJ **679** (2008).