Planetary and Space Science 100 (2014) 32–39

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Modeling the infrared interstellar extinction

Shu Wang [a,b,*], Aigen Li [b,*], B.W. Jiang [a,b,*]

[a] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[b] Department of Physics and Astronomy, University of Missouri, Columbia, MO 65211, USA

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form
21 March 2014
Accepted 24 March 2014
Available online 5 April 2014

Keywords:
Infrared
Extinction
Dust
Model

ABSTRACT

How dust scatters and absorbs starlight in the interstellar medium (ISM) contains important clues about the size and composition of interstellar dust. While the ultraviolet (UV) and visible interstellar extinction is well studied and can be closely fitted in terms of various dust mixtures (e.g., the silicate–graphite mixture), the infrared (IR) extinction is not well understood, particularly, the mid-IR extinction in the 3–8 μm wavelength range is rather flat (or "gray") and is inconsistent with the standard Mathis, Rumpl, & Nordsieck (MRN) silicate–graphite dust model. We attempt to reproduce the flat IR extinction by exploring various dust sizes and species, including amorphous silicate, graphite, amorphous carbon and iron. We find that the flat IR extinction is best explained in terms of micrometer-sized amorphous carbon dust which consumes ~ 60 carbon atoms per million hydrogen atoms (i.e., C/H ≈ 60 ppm). To account for the observed UV/visible and near-IR extinction, the silicate–graphite model requires Si/H ≈ 34 ppm and C/H ≈ 292 ppm. We conclude that the extinction from the UV to the mid-IR could be closely reproduced by a mixture of submicrometer-sized amorphous silicate dust, submicrometer-sized graphitic dust, and micrometer-sized amorphous carbon dust, at the expense of excess C available in the ISM (i.e., this model requires a solid-phase C abundance of C/H $\approx$ 352 ppm, considerably exceeding what could be available in the ISM).

1. Introduction

The interstellar extinction is one of the primary sources of information about the interstellar dust size and composition. The interstellar extinction varies from one sightline to another in the ultraviolet (UV) and the optical wavelength range. This variation in the Milky Way galaxy can be described by a single parameter, i.e., R_V (Cardelli et al., 1989; hereafter CCM).[1] The average extinction law for the Galactic diffuse interstellar medium (ISM) corresponds to $R_V \approx 3.1$. Based on the interstellar extinction curve observed for the diffuse ISM $R_V \approx 3.1$, Mathis et al. (1977) constructed a simple interstellar dust model to fit the interstellar extinction observed over the wavelength range of $0.11\ \mu m < \lambda < 1\ \mu m$. This classic model – known as the "MRN" model – consists of silicate and graphite grains[2] and takes a simple power-law size distribution $dn/da \propto a^{-\alpha}$ with $\alpha \approx 3.5$ for the size range of $50\ Å < a < 0.25\ \mu m$, where a is the radius of the dust which is assumed to be spherical.[3] This model was

* Corresponding authors.
E-mail addresses: shuwang@mail.bnu.edu.cn (S. Wang), lia@missouri.edu (A. Li), bjiang@bnu.edu.cn (B.W. Jiang).

[1] $R_V \equiv A_V/E(B-V)$ is the total-to-selective extinction ratio, where $E(B-V) \equiv A_B - A_V$ is the reddening which is the difference between the extinction in the blue band (A_B) and the extinction in the visual band (A_V).

[2] Hoyle and Wickramasinghe (1962) first proposed that graphite grains of sizes a few times 0.01 μm could condense in the atmospheres of cool N-type carbon stars, and these grains would subsequently be driven out of the stellar atmospheres and injected into the interstellar space by the stellar radiation pressure. Similarly, Kamijo (1963) suggested that nanometer-sized SiO_2 grains could condense in the atmospheres of cool M-type stars. Gilman (1969) argued that grains around oxygen-rich cool giants could mainly be silicates such as Al_2SiO_5 and Mg_2SiO_4. Silicates were first detected in emission in M stars (Woolf and Ney, 1969; Knacke et al., 1969). After blown out of the stellar atmospheres and injected into the interstellar space, silicates could become an interstellar dust component. Hoyle and Wickramasinghe (1969) first modeled the interstellar extinction in terms of a mixture of silicate grains of radii $\sim 0.07\ \mu m$ and graphite grains of radii $\sim 0.065\ \mu m$. Wickramasinghe and Nandy (1970) found that a mixture of silicate, graphite, and iron grains achieved a rough fair fit to the interstellar extinction curve at $\lambda^{-1} < 8\ \mu m^{-1}$.

[3] To be precise, the MRN model actually derived a *wider* size range of $50\ Å < a < 1\ \mu m$ for the graphite component and a *narrower* size range of $0.025\ \mu m < a < 0.25\ \mu m$ for the silicate component (and for other components such as SiC, iron and magnetite), with $\alpha \approx 3.3$–3.6. In the literature, the MRN model is customarily taken to be a mixture of silicate and graphite with $\alpha = 3.5$ and $50\ Å < a < 0.25\ \mu m$. This is probably because (1) in their Fig. 4 the demonstrated model fit to the observed UV/visible extinction was provided by the olivine–graphite mixture with $\alpha = 3.5$ and $50\ Å < a < 0.25\ \mu m$ for both dust components; and (2) Draine and Lee (1984) also derived $\alpha = 3.5$ and $50\ Å < a < 0.25\ \mu m$ for both dust components using improved optical constants for these two substances. The sudden cutoff at $a_{min} = 50\ Å$ and $a_{max} = 0.25\ \mu m$ is not physical. Kim et al. (1994) and WD01 adopted a more smooth size distribution function which extends

http://dx.doi.org/10.1016/j.pss.2014.03.018
0032-0633/

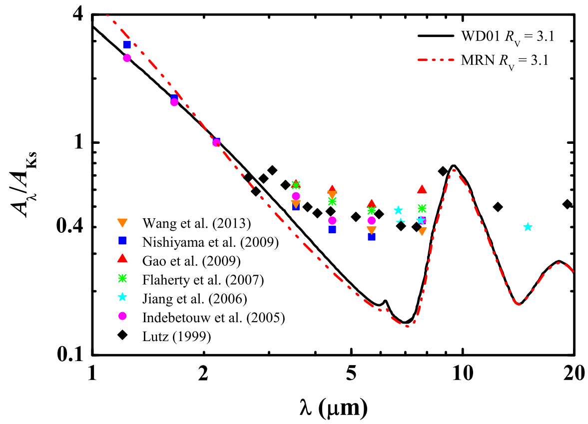

Fig. 1. Comparison of the IR extinction observed for various interstellar regions with that predicted from the MRN (red dot-dashed line) and WD01 (black solid line) silicate–graphite models for the diffuse ISM of which the UV/optical extinction is characterized by $R_V \approx 3.1$. The little bump at 6.2 μm arises from the C–C stretching absorption band of PAHs (see Li and Draine, 2001). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

further developed by Draine and Lee (1984) who extensively discussed the optical properties of "astronomical" silicate and graphite materials. Subsequent developments were made by Draine and his coworkers (Weingartner and Draine, 2001 [hereafter WD01], Li and Draine, 2001) who extended the silicate–graphite grain model to explicitly include polycyclic aromatic hydrocarbon (PAH) molecules to explain the so-called "unidentified infrared emission" (UIE) bands at 3.3, 6.2, 7.7, 8.6, and 11.3 μm (see Léger and Puget, 1984; Allamandola et al., 1985).

With the wealth of available data from space-borne telescopes (e.g., *Infrared Space Observatory* [ISO] and Spitzer Space Telescope) and ground-based surveys (e.g., *Two Micron All Sky Survey* [2MASS]) in the near- and mid-infrared, in recent years we have seen an increase in interest in the infrared (IR) extinction. Understanding the effects of dust extinction in the IR wavelengths is important to properly interpret these observations. While the UV/optical extinction has been extensively observed for a wide variety of environments and modeled in terms of various dust models, our understanding of the near- and mid-IR extinction is still somewhat poor and controversial, despite that in this spectral domain many advances have been made in the past few years (see Section 1 of Wang et al., 2013).

As shown in Fig. 1, WD01 silicate–graphite grain model predicts a power-law of $A_\lambda \propto \lambda^{-1.74}$ for the IR extinction at $1\,\mu m < \lambda < 7\,\mu m$, while the MRN model predicts a steeper power-law of $A_\lambda \propto \lambda^{-2.02}$.[4] The model IR extinction curves reach their minimum at ~7 μm where the extinction power-law intersects the blue-wing of the 9.7 μm silicate absorption band.

Rieke and Lebofsky (1985) measured the IR extinction from 1 μm to 13 μm for the lines of sight toward *o* Sco, a normal A5 II star behind the edge of the ρ Oph cloud obscured by $A_V \approx 2.92$ mag,[5] and toward a number of stars in the galactic center (GC). Rieke and Lebofsky (1985) derived a power-law of $A_\lambda \propto \lambda^{-1.62}$ for $1\,\mu m < \lambda < 7\,\mu m$ for *o* Sco and the GC sources. Draine (1989) compiled the IR extinction observed for a range of galactic regions including diffuse clouds, molecular clouds, and HII regions. He derived a power-law of $A_\lambda \propto \lambda^{-1.75}$ for $1\,\mu m < \lambda < 7\,\mu m$. More recently, Bertoldi et al. (1999) and Rosenthal et al. (2000) also derived a power-law extinction of $A_\lambda \propto \lambda^{-1.7}$ for $2\,\mu m < \lambda < 7\,\mu m$ for the Orion molecular cloud (OMC).[6]

However, numerous recent observations suggest the mid-IR extinction at $3\,\mu m < \lambda < 8\,\mu m$ to be almost *universally* flat or "gray" for both diffuse and dense environments (see Section 1.4 of Wang et al., 2013 for a summary), much flatter than that predicted from the MRN or WD01 silicate–graphite model for R_V=3.1 (see Fig. 1).

Lutz et al. (1996) derived the extinction toward the GC star Sgr A* between 2.5 μm and 9 μm from the H recombination lines. They found that the GC extinction shows a flattening of A_λ in the wavelength region of $3\,\mu m < \lambda < 9\,\mu m$, clearly lacking the pronounced dip at ~7 μm predicted from the R_V=3.1 silicate–graphite model (see Fig. 1). This was later confirmed by Lutz (1999), Nishiyama et al. (2009), and Fritz et al. (2011).

Indebetouw et al. (2005) used the photometric data from the *2MASS* survey and the *Spitzer*/GLIMPSE Legacy program to determine the IR extinction. From the color excesses of background stars, they derived the ~1.25–8 μm extinction laws for two very different lines of sight in the Galactic plane: the l=42° sightline toward a relatively quiescent region, and the l=284° sightline which crosses the Carina Arm and contains RCW 49, a massive star-forming region. The extinction laws derived for these two distinct Galactic plane fields are remarkably similar: both show a flattening across the 3–8 μm wavelength range, consistent with that derived by Lutz et al. (1996) for the GC.

Jiang et al. (2006) derived the extinction at 7 and 15 μm for more than 120 sightlines in the inner Galactic plane based on the ISOGAL survey data and the near-IR data from DENIS and 2MASS, using RGB tip stars or early AGB stars (which have only moderate mass loss) as the extinction tracers. They found the extinction well exceeding that predicted from the MRN or WD01 R_V=3.1 model.

Flaherty et al. (2007) obtained the mid-IR extinction laws in the *Spitzer*/IRAC bands for five nearby star-forming regions. The derived extinction laws at ~4–8 μm are flat, even flatter than that of Indebetouw et al. (2005).

Gao et al. (2009) used the *2MASS* and *Spitzer*/GLIPMSE data to derive the extinction in the four IRAC bands for 131 GLIPMSE fields along the Galactic plane within $|l| \leq 65°$. Using red giants and red clump giants as tracers, they also found the mean extinction in the IRAC bands to be flat.

Wang et al. (2013) determined the mid-IR extinction in the four *Spitzer*/IRAC bands of five individual regions in Coalsack, a nearby starless dark cloud, spanning a wide variety of interstellar environments from diffuse and translucent to dense clouds. They found that all regions exhibit a flat mid-IR extinction.

All these observations appear to suggest a "universally" flat extinction law in the mid-IR, with little dependence on environments.[7] While rapid progress has been made in observationally determining the mid-IR extinction and numerous IR extinction

(*footnote continued*)
smoothly to $a > 1$ μm. But the dust with $a > 1$ μm takes only a negligible fraction of the total dust mass.

[4] At $\lambda > 7$ μm, the extinction increases because of the 9.7 μm silicate Si–O stretching absorption band.

[5] The extinction toward *o* Sco at $\lambda > 0.55$ μm can be well described by the R_V=3.1 extinction law. At $\lambda < 0.55$ μm, the observed colors of *o* Sco are much bluer than expected from those of a normal A5 II star obscured by $A_V = 2.92$ mag with

(*footnote continued*)
the R_V=3.1 extinction law, leading to the assignment of $R_V \approx 4.0$ (see Rieke and Lebofsky, 1985).

[6] The OMC extinction also displays an absorption band at 3.05 μm attributed to water ice.

[7] We should note that an "universally" flat mid-IR extinction law does not necessarily mean an identical mid-IR extinction law for all regions, instead, it merely means a flattening trend of A_λ with λ in the mid-IR. Chapman et al. (2009), McClure (2009), and Cambrésy et al. (2011) found that the shape of the mid-IR extinction law appears to vary with the total dust extinction. But also see Román-