

Dark dust

II. Properties in the general field of the diffuse ISM

R. Siebenmorgen^{1b}

European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching b. München, Germany
 e-mail: Ralf.Siebenmorgen@eso.org

Received 25 April 2022 / Accepted 18 November 2022

ABSTRACT

Distance estimates derived from spectroscopy or parallax have been unified by considering extinction by large grains. The addition of such a population of what is called dark dust to models of the diffuse interstellar medium is tested against a contemporary set of observational constraints. By respecting representative solid-phase element abundances, the dark dust model simultaneously explains the typical wavelength-dependent reddening, extinction, and emission of polarised and unpolarised light by interstellar dust particles between far-UV and millimeter wavelengths. The physical properties of dark dust were derived. Dark dust consists of micrometer-sized particles. These particles have recently been detected in situ. Dark dust provides significant wavelength-independent reddening from the far-UV to the near-infrared. Light absorbed by dark dust is re-emitted in the submillimeter region by grains at dust temperatures of 8–12 K. This very cold dust has frequently been observed in external galaxies. Dark dust contributes to the polarisation at $\gtrsim 1$ mm to $\sim 35\%$ and marginally at shorter wavelengths. Optical constants for silicate dust analogous were investigated. By mixing 3% in mass of $\text{Mg}_{0.8}\text{Fe}_{0.2}^{2+}\text{SiO}_3$ to $\text{MgO}-0.5\text{SiO}_2$, a good fit to the data was derived that can still accommodate up to 5–10% of mass in dark dust. The additional dimming of light by dark dust is unexplored when supernova Ia light curves are discussed and in other research. Previous models that ignored dark dust do not account for the unification of the distance scales.

Key words. dust, extinction – polarization – infrared: ISM – stars: distances

1. Introduction

Physical properties of dust in the diffuse interstellar medium (ISM) are derived by comparing models with observational constraints. Two classes of models emerged over the years: models that employ distinct grain populations (Mathis et al. 1977; Draine & Lee 1984; Desert et al. 1990; Weingartner & Draine 2001; Zubko et al. 2004; Compiègne et al. 2011; Siebenmorgen et al. 2014), or models that use a mixture of different grain constituents forming composite particles (Hage & Greenberg 1990; Mathis & Whiffen 1989; Ossenkopf 1991; Krügel & Siebenmorgen 1994; Greenberg et al. 1995; Voshchinnikov 2012; Jones et al. 2013, 2017; Siebenmorgen et al. 2014; Köhler et al. 2015; Ysard et al. 2015; Guillet et al. 2018; Draine & Hensley 2021a). The current observational status of ISM dust characteristics after the Planck mission (Planck Collaboration XVII 2014) has been reviewed by Hensley & Draine (2021). Dust models shall agree with several major observations as listed below.

1. The solid-phase element abundances in the medium out of which the dust is made (Hensley & Draine 2021).
2. The reddening curves in the Milky Way (Fitzpatrick & Massa 2007; Gordon et al. 2009; Fitzpatrick et al. 2019; Siebenmorgen et al. 2022).
3. The diffuse Galactic dust emission that has been observed in the wavelength range from a few micrometers (μm) up to several millimeters (mm) by the space missions ISO¹, AKARI, Spitzer, WMAP², DIRBE³, and Planck (Planck Collaboration XVII 2014).
4. The optical/near-infrared (NIR) starlight polarisation (Serkowski et al. 1975), which is due to the dichroic

extinction of aligned non-spherical dust particles (Hong & Greenberg 1980; Krügel 2008; Draine & Fraisse 2009; Siebenmorgen et al. 2014; Voshchinnikov 2012).

5. The polarised emission spectrum of the same grains, which is predominantly observed by Planck Collaboration XII (2020). Strikingly, previous dust models in the pre-Planck era systematically under-predicted the observed submillimeter (submm) and mm emission of unpolarised light from about 0.3–3 mm, and did not explain the flatness of the polarised dust emission spectrum in that wavelength range.
6. In addition, the unification of spectroscopically derived distances with the parallax is not completed.

However, previous dust models failed to simultaneously explain all observational constraints that have been available in the post-Planck era (Ysard 2020), except for the model by Draine & Hensley (2021a), in which the optical constants of amorphous silicates were modified to fit the Planck data.

For a star, the spectro-photometric distance D_{SpL} shall agree with the distance D_{Gaia} derived from the parallax. Geometric distances using Gaia (Gaia Collaboration . 2016) as derived by Bailer-Jones et al. (2018, 2021) show a fractional error of $\sim 5\%$ for OB stars with available reddening curves at distances smaller than 2 kpc. The photometric distance of a star is connected via the apparent m_V and absolute magnitude M_V , and the dust extinction A_V along that sightline: $\log D_{\text{SpL}} = 0.2 (m_V - M_V - A_V + 5)$ pc. Photometric distances require an accurate calibration of the spectral type and luminosity class (SpL) of the star, allowing the derivation of M_V and A_V (Eq. (4)). The original SpL estimates of OB stars (Walborn 1971; Walborn & Fitzpatrick 1990) have gained significantly in precision using results of the Galactic O star spectroscopic survey (Maíz-Apellániz et al. 2004) with SpL updates by Sota et al. (2011, 2014) and applying quantitative spectral classification schemes using high-resolution

¹ Infrared Space Observatory (Kessler et al. 1996).

² Wilkinson Microwave Anisotropy Probe (Spergel et al. 2003).

³ Diffuse Infrared Background Experiment (Dwek et al. 1997).

optical spectroscopy (Markova et al. 2011; Martins 2018). Standard grids of absolute magnitudes for OB stars are provided (Bowen et al. 2008; Pecaut & Mamajek 2013)⁴, along with high-quality extinction estimates (Maíz Apellániz & Barbá 2018; Siebenmorgen et al. 2022). This progress enables computing spectro-photometric distances of OB stars at fractional precision of $\sim 15\%$ for the nearby (2 kpc) sample. Photometric versus parallax distance estimates to Galactic OB stars were discussed by Shull & Danforth (2019) and reveal larger uncertainties at larger distances. In the nearby sample, the spectroscopic distances show a systematic overestimate with a dispersion above these errors (Siebenmorgen et al. 2020). The two distance estimates of the same source must agree.

Trumpler (1930) already included a constant, wavelength-independent (non-selective) extinction component in the optical in the original form of the photometric equation, in addition to the wavelength-dependent (selective) interstellar extinction. He proposed that light may be obscured by large (meteoritic) particles. Large micrometer-sized dust particles are frequently found in circumstellar shells (Strom et al. 1971; Jones 1972; Lanz et al. 1995; Steinacker et al. 2015; Kataoka et al. 2017), Herbig stars (Dunkin & Crawford 1998), η Car (Andriesse et al. 1978), and other evolved stars (Scicluna et al. 2015, 2022). Grains larger than $2\mu\text{m}$ have been seen in scattering-light haloes around X-ray sources (Witt et al. 2001), and grains as large as $\sim 4\mu\text{m}$ have been suggested for V404 Cygni by Heinz et al. (2016). The emission from $100\mu\text{m}$ particles accounting for the observed submm fluxes from evolved giants were derived by Jura et al. (2001). Maercker et al. (2022) reported that for carbon stars, $\sim 2\mu\text{m}$ sized grains preferentially survive the interaction regions between the asymptotic giant branch wind and the ISM. These large grains later act as seeds for grain growth in the ISM.

Distance estimates of the Orion Trapezium star HD 37020 using spectral type-luminosity distance D_{SpL} are a factor 2.5 larger than the Ca II or VLBI parallax distance estimates (Krełowski et al. 2016). For several nearby (≤ 400 pc) OB stars, a significant overestimate of the spectroscopic distance over the HIPPARCOS parallax is reported by Skórzyński et al. (2003). If the parallax has been correctly measured, the derived absolute magnitudes of these stars appear too faint. So-called super large grains are suggested for the additional weakening of the observed brightness of these stars. The column density of this very large grain population is well correlated with the strength of DIB 6367 Å and DIB 6425 Å and therefore appears distributed along the sightline through the diffuse ISM. The spectral type-luminosity distances of 132 OB stars were compared to those derived by *Gaia* up to $D_{\text{Gaia}} < 2$ kpc. For $\sim 10\%$ of that sample $D_{\text{SpL}}/D_{\text{Gaia}} \gtrsim 2$ (Siebenmorgen et al. 2020). These two distance estimates were unified by introducing 0.3–0.7 mag reddening by what is called dark dust⁵. Extensive clouds of dark gas were weighted using Fermi-LAT γ -ray data by Widmark et al. (2022) and emerge in the cold ISM. The hidden dark dust component appears in sightlines that are connected to the cold⁶ ISM. A sticking of smaller grains into larger units might be favoured in cold ISM environments. A circumstellar nature of dark dust towards these stars is excluded from inspecting WISE

imaging between 3 and $22\mu\text{m}$ (Siebenmorgen et al. 2020). Micrometer-sized particles from the diffuse ISM were measured in situ from the Ulysses, Galileo, and Stardust space probes to the outer Solar System (Landgraf et al. 2000; Westphal et al. 2014; Krüger et al. 2015).

The emission of dark dust as a new component of the diffuse ISM should be observable in the submm to mm wavelength range. It will absorb a fraction of the interstellar radiation field, ISRF (Mathis et al. 1983). Because these grains are large, they are cold and will emit at long wavelengths. Originally very cold (≤ 15 K) dust emission was detected in the general field of the ISM of non-active galaxies (Krügel et al. 1998; Siebenmorgen et al. 1999) and in our Galaxy towards high-density regions (Chini et al. 1993). More recently, the *Herschel* KINGFISH (Kennicutt et al. 2011) and Dwarf Galaxy (Madden et al. 2013) surveys reported that 35 out of 78 galaxies have excess emission at 0.5 mm that cannot be explained by a single modified black-body temperature component with a dust emissivity spectral index of two (Rémy-Ruyer et al. 2013). Other galaxies, for example, Haro 11 (Galliano et al. 2005; Galametz et al. 2009), show the excess emission at even longer wavelengths in the mm range and were missed by *Herschel* surveys. The excess emission is due to very cold dust at temperatures as low as 10 K. A solution to explain the submm/mm excess emission is often favoured by ad hoc adjustments of the emissivity law of the grains (Rémy-Ruyer et al. 2013; Guillet et al. 2018). This can be derived by changes in the porosity or shape, or by adjustments of the optical constants (Draine & Hensley 2021a). Models changing the spectral index of the dust emissivity do not consider the issue of distance unification.

In this paper, a model for the general field in the diffuse ISM is described that simultaneously accounts for observations of solid-phase elemental abundances, average Milky Way reddening, IR to mm emission at high Galactic latitudes, average Milky Way polarised extinction, and polarised emission by dust. A particular feature is the inclusion of dark dust as an additional dust population that accounts for the very cold emission that is detected in the submm to mm range. Dark dust may solve the puzzle between discrepant spectroscopic and parallax-derived distance estimates. First, the observational basis is specified, then the dust model is described, and a vectorized fitting procedure of the 11-parameter dust model to the observational constraints is detailed. Results are presented and show the overall success of the model in fitting the data and deriving the physical properties of dark dust. Particular attention is given to the use of optical constants of amorphous silicates (Demyk et al. 2022). The main findings are summarized in the conclusions.

2. Observations

2.1. Solid-phase abundances

Depletion of elements from the gas into dust was estimated by Voshchinnikov & Henning (2010) as the difference between abundances in the Sun (Asplund et al. 2009) and that of the gas (Jenkins 2009). Elemental depletion is used to infer dust compositions, and some form of grains with silicate and carbon is widely accepted. Abundances of element [X] to that of hydrogen [H] were summarized by Hensley & Draine (2021) for the gas and the dust phase, respectively. The most abundant elements in dust are O (249 ± 94), C (126 ± 56), Mg (46 ± 5), Fe (43 ± 4), Si (38 ± 3), S (7.6), Al (3.4), Ca (3.2), and Ni (2.0), where numbers in parenthesis give [X]/[H] in parts per million (ppm). An over-abundance of O in the dust was noted, and upper limits of the 16 and $22\mu\text{m}$ bands of iron oxides indicate that

⁴ <http://www.pas.rochester.edu/~emamajek/>

⁵ The dark dust terminology was introduced as it follows the unveiling of dark gas by Grenier et al. (2005) because gas and dust are intimately mixed in the diffuse ISM. It describes a mysterious, dimmed, and hidden nebula.

⁶ Sightlines are classified to be dominated by the cold ISM when the line intensity ratio of CH 4300 Å to CH⁺ 4233 Å is greater than one and CN 3875 Å detected (Siebenmorgen et al. 2020).

most of the Fe remain unexplained as well (Draine & Hensley 2021a). However, the Fe abundance is insufficient to form large grains (Zhukovska et al. 2018). Fe particles heated by the ISRF contribute to the emission at $\sim 60\mu\text{m}$ (Fischera 2004). Draine & Hensley (2021a) showed that the absorption cross section remains unaltered in the IR – mm when the available Fe in form of impurities is included in large particles.

Dust abundances are uncertain, and estimates of the C and Si abundance in dust scatter by 50%. Mulas et al. (2013) reported an average of $[\text{C}]/[\text{H}] = 145$ ppm. The Si abundance in the dust was estimated by Sofia & Meyer (2001) to be 18 ± 9 ppm, while Nieva & Przybilla (2012) derived 32 ± 3 ppm. Voshchinnikov & Henning (2010) found a sharp difference in the dust abundances for sightlines located at low and high Galactic latitudes and reported an average abundance of $[\text{Si}]/[\text{H}] = 23 \pm 5$ ppm.

Absorption and emission signatures of the dust provide important constraints on the composition. The $2175\text{\AA}$ extinction bump is a striking feature, where graphite and polycyclic aromatic hydrocarbons (PAHs; Allamandola et al. 1989) have strong electronic transitions. The IR contains conspicuous emission bands at 3.3 , 6.2 , 7.7 , 8.6 , 11.3 , and $12.7\mu\text{m}$, as well as a wealth of weaker bands in the $12\text{--}24\mu\text{m}$ region. These bands are ascribed to vibrational transitions in PAH molecules, which are planar structures that consist of benzol rings to which hydrogen is attached. PAH feature strengths depend on the hardness of the exciting radiation field and on the ionisation or hydrogenation coverage of the molecules.

Absorption features in the diffuse ISM between 3 and $8\mu\text{m}$ are interpreted as being due to either carbonaceous material (Mennella et al. 2003) or, guided by laboratory spectra, by ices mixed with silicates (Potapov et al. 2021). Dust models including interstellar ice mixtures were presented by Siebenmorgen & Gredel (1997). Solid-state water mixed with silicates would explain a good fraction of the unaccounted oxygen depletion in the diffuse ISM (Potapov et al. 2021). A comparison of future JWST observations with laboratory spectra is needed to confirm the existence of solid water in the diffuse ISM. Ices are not further considered in this study.

The 9.7 and $18\mu\text{m}$ broadband features are assigned to Si-O stretching and O-Si-O bending modes of silicate grains, respectively. A comparison of the observed band profiles and laboratory spectra favours amorphous rather than crystalline silicates. The detection of the $11.1\mu\text{m}$ absorption band is intriguing. This band is attributed in the atlas of ground-based mid-infrared (MIR) spectra by Do-Duy et al. (2020) to forsterite, providing a mass abundance of crystalline silicates of $\sim 2\%$ in the diffuse ISM. Olivine ($\text{Mg}_{2-x}\text{Fe}_{2-2x}\text{SiO}_4$ has $x \sim 0.8$) was detected in AGB and T Tauri stars and in comet Hale-Bopp (Henning 2010). The silicate stoichiometry and grain geometry can be revealed by MIR spectro-polarimetry (Sect. 2.4). As nominal composition, Draine & Hensley (2021a) adopted $\text{Mg}_{1.3}(\text{Fe},\text{Ni})_{0.3}\text{SiO}_{3.6}$ with a molecular weight of $\mu = 134.5$. In this structure, the silicate grain abundance is limited by Mg with a dust abundance ratio $[\text{C}]/[\text{Si}] \sim [\text{C}] 1.3/[\text{Mg}] \sim 3.5$. To accommodate the reported large scatter of $\sim 50\%$ in the solid-phase element abundances, the dust models must respect a limit of the dust abundance ratio of

$$[\text{C}]/[\text{Si}] \lesssim 5.25. \quad (1)$$

2.2. Reddening and extinction

The interstellar reddening is derived by measuring the flux ratio of a reddened and an unreddened star with the same SpL

luminosity class, for instance, with the standard pair method (Stecher 1965). The flux of a star is derived from the spectral luminosity $L(\lambda)$, the distance D , and the extinction optical depth $\tau(\lambda)$, which is due to the absorption and scattering of photons along the sightline, excluding emission. The observed flux of the reddened star is given by

$$F(\lambda) = \frac{L(\lambda)}{4\pi D^2} e^{-\tau(\lambda)}. \quad (2)$$

In photometry, it is customary to express the flux of an object by the apparent magnitude, which is related to the flux through $m(\lambda) = 2.5 \log_{10}(F(\lambda)/w_\lambda)$ and w_λ as the zero-point of the photometric system. The difference in magnitudes between two stars is $\Delta m(\lambda) = 1.086 \times (\tau(\lambda) + 2 \log_{10}(D/D_0))$. Unfortunately, distances to hot, early-type stars, which are commonly used to measure interstellar extinction, are often subject to large errors (Siebenmorgen et al. 2020). I therefore rely on relative measurements of two wavelengths and define the colour excess $E(\lambda - \lambda') = \Delta m(\lambda) - \Delta m(\lambda')$. The reddening curve $E(\lambda)$ is traditionally represented by a colour excess and normalisation to avoid the uncertainties between the two distances,

$$E(\lambda) = \frac{E(\lambda - V)}{E(B - V)} = \frac{A_\lambda - A_V}{A_B - A_V} = \frac{\tau_\lambda - \tau_V}{\tau_B - \tau_V}. \quad (3)$$

For the V and B band, $E(V) = 0$ and $E(B) = 1$. The extinction in magnitudes at wavelength λ is denoted by $A(\lambda)$. Some extrapolated estimate of the visual extinction A_V is obtained from photometry. This requires measuring $E(B - V)$ and extrapolating the reddening curve to infinite wavelengths $E(\infty)$. In practice, $E(\lambda - V)$ is derived at the longest wavelength, which is not contaminated by any type of emission. From this wavelength, for example, the H-band, one extrapolates to infinite wavelengths assuming some prior shape of $E(\lambda)$ and hence estimate $E(\infty, V)$. By introducing the ratio of the total-to-selective extinction,

$$R_V = \frac{A_V}{E(B - V)}, \quad (4)$$

where $E(\infty) = -R_V$. The total-to-selective extinction can also be written using Eq. (3) or applying a dust model as

$$R_V = \frac{\tau_V}{\tau_B - \tau_V} = \frac{K_V}{K_B - K_V}, \quad (5)$$

where $K = K_{\text{abs}} + K_{\text{sca}}$ is the extinction cross section, which is the sum of the total absorption and scattering cross section of the dust. The relation between reddening and extinction is

$$\frac{\tau(\lambda)}{\tau_V} = \frac{K(\lambda)}{K_V} = \frac{E(\lambda)}{R_V} + 1. \quad (6)$$

The International Ultraviolet Explorer (IUE) operated between 0.185 and $0.33\mu\text{m}$, and the Far Ultraviolet Spectroscopic Explorer (FUSE) observed between 0.119 and $0.905\mu\text{m}$. IUE and FUSE provide the legacy of far-UV (FUV) spectra with a total of 895 reddening curves towards more than 568 early-type (OB) stars (Valencic et al. 2004; Fitzpatrick & Massa 2007; Gordon et al. 2009). The database of available reddening curves was scrutinized against systematic errors by the following means: (1) IUE/FUSE spectra were verified to

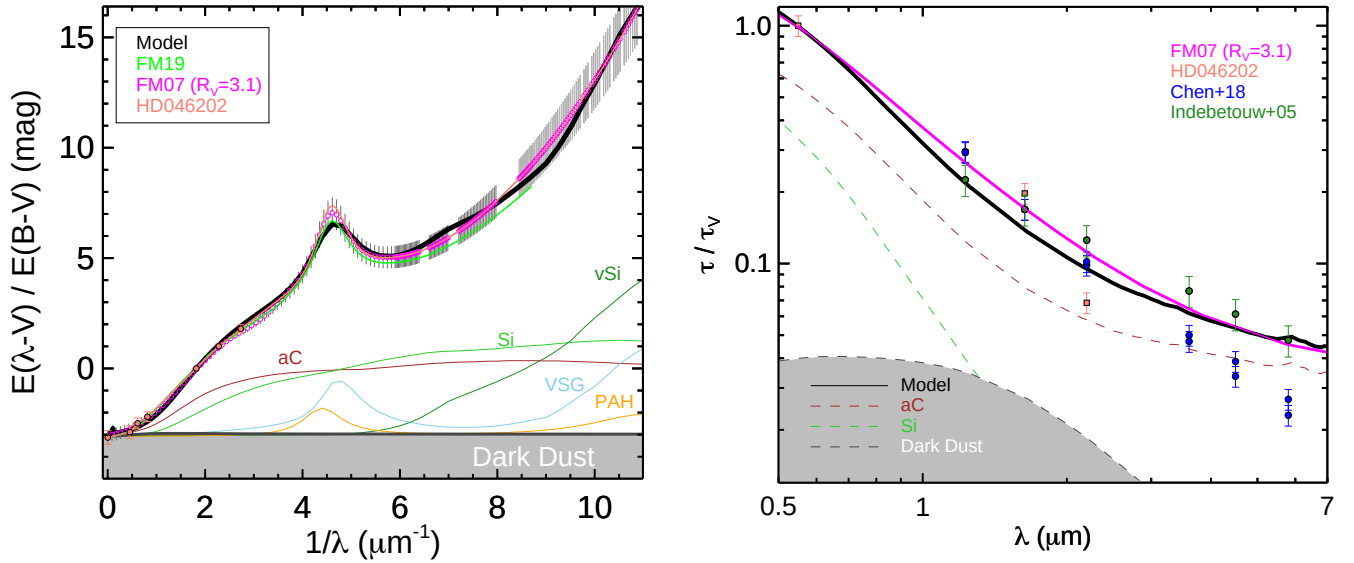


Fig. 1. Reddening (left) and extinction (right) of the diffuse ISM (Fitzpatrick & Massa 2007; Fitzpatrick et al. 2019; Indebetouw et al. 2005; Chen et al. 2018) and of HD 046202 (Gordon et al. 2009). Model (black) with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ (Table 1) and individual dust components as labelled. The area in grey shows the contribution of the dark dust.

include only a single star in the observing aperture and not beside the program star and other almost equally bright objects. (2) Although most early-type stars are binaries (Chini et al. 2012), their reddening curves are generally derived assuming a single star. Whenever the companion contributes significantly to the total flux of the system, the derived extinction includes large systematic errors. (3) A large fraction of the OB stars show emission components above the photosphere in the IR (Siebenmorgen et al. 2018a; Deng et al. 2022), which prohibits deriving meaningful reddening in the IR. (4) Reddening curves are derived assuming steady stellar systems. Stellar variability will thus systematically impact the derived reddening. Stars with detected variability between ground-based and HIPPARCOS V -band photometry (≥ 0.1 mag), significant $B - V$ colour changes, or *Gaia* G -band photometry of more than (≥ 0.033 mag) were rejected. (5) Some stars show inconsistencies in the *Gaia* parallaxes between data release two (Gaia Collaboration 2018) and data release three (Gaia Collaboration 2020) that are not instrumental, so that their reddening curves were declared as spurious. (6) Finally, the quality of the derived reddening curve critically depends on the fidelity of the SpL estimate. The SpL determination of fast rotators is highly uncertain, and UV spectral diagnostics indicate considerably earlier SpL (hotter) classifications than optically assigned SpL. Reddening curves with largely deviating SpL assignments were ignored. All these systematic effects impact the derivation more dramatically at $\lambda \gtrsim 1 \mu\text{m}$ and the extinction more than the reddening. In total, 48 stars with one or more reddening curves passing the rejection criteria were available, 21 of which were classified as multi-component sightlines and 27 as single-cloud sightlines (Siebenmorgen et al. 2020). The reddening curves in the ISM show significant variations from sightline to sightline, and the derived total-to-selective extinction is between $2 \lesssim R_V \lesssim 6.4$. For the same star, the published R_V , which is mostly extrapolated from *JHK* photometry, typically scatters by 10%. Even in the high-quality sample, the peak-to-peak scatter in R_V estimates of the same star are up to ± 0.6 . The scatter might be reduced by detailed physical modelling of the dust, applying Eq. (5). Whenever possible, the reddening instead of the extinction curve is discussed.

For the diffuse ISM, a mean reddening of $E(B - V) = 0.45$ mag and a median and mean value of $R_V = 3.22$ and 2.99 ± 0.27 were derived by Fitzpatrick & Massa (2007); Wang & Chen (2019) reported $R_V = 3.16$, and Voshchinnikov (2004); Fitzpatrick et al. (2019) gave $A_V \sim 3.1$ $E(B - V)$. I adopted $R_V = 3.1$, as in Hensley & Draine (2021). The mean reddening curve of the Milky Way was derived for $1/\lambda \lesssim 18 \mu\text{m}^{-1}$ by Fitzpatrick & Massa (2007) and Fitzpatrick et al. (2019), and both are shown together with the reddening curve of HD 046202 (Gordon et al. 2009) in Fig. 1. The reddening curve of this star perfectly matches the mean curve derived from IUE and FUSE. Reddening in spectral regions close to the wind lines at 6.5 and $7.1 \mu\text{m}^{-1}$ and Ly- α at $8 \mu\text{m}^{-1} \leq x \leq 8.45 \mu\text{m}^{-1}$, or with apparent instrumental noise at $x \lesssim 3.6 \mu\text{m}^{-1}$ were ignored. Overall, the typical error in the derived reddening is $\sim 10\%$. Various mean extinction curves of the diffuse ISM between 0.5 and $7 \mu\text{m}$ are also shown in Fig. 1. The large scatter that increases towards longer wavelengths is clearly visible.

2.3. Diffuse Galactic dust emission

Diffuse emission of the ISM from dust grains heated by the ambient ISRF has been observed from the NIR through the microwave region. The dust emission of the diffuse ISM is not uniform across the sky, and there is evidence that the properties of the dust vary, as do the spectral distribution and strength of the ISRF that heats the dust (Fanciullo et al. 2015). Observations of this component for high Galactic latitude ($|b| \gtrsim 25^\circ$) from the Cosmic Background Explorer using DIRBE data are given by Dwek et al. (1997) and from the Planck Collaboration XXI (2015). A colour-corrected composite spectrum with error estimates is tabulated by Hensley & Draine (2021). The emission spectrum is shown in Fig. 2.

2.4. Starlight and far-IR polarisation

Stellar light that passes a cloud of moderate extinction by aligned grains becomes linearly polarised. From the FUV to the NIR, between 0.12 and $1.6 \mu\text{m}$, the polarisation curves are fit by an

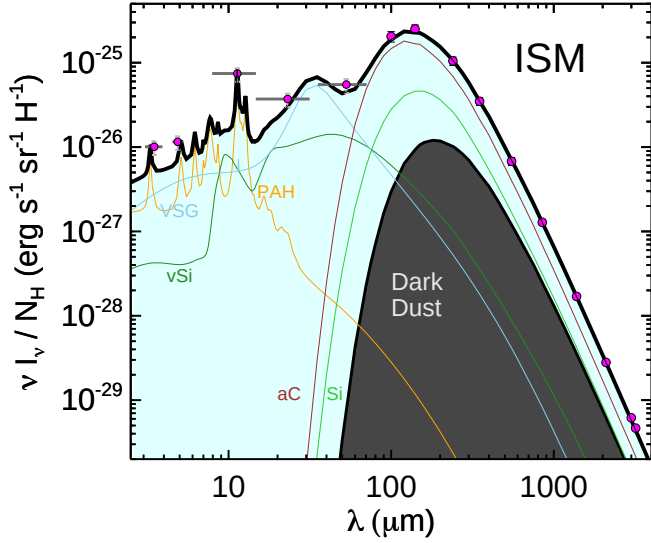


Fig. 2. Dust emission of the diffuse ISM observed at high Galactic latitudes and normalised per H atom by [Dwek et al. \(1997\)](#) and [Planck Collaboration XXI \(2015\)](#) and as tabulated by [Hensley & Draine \(2021\)](#). Model (black) with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ (Table 1) and individual dust components as labelled. The area in grey shows the contribution of the dark dust.

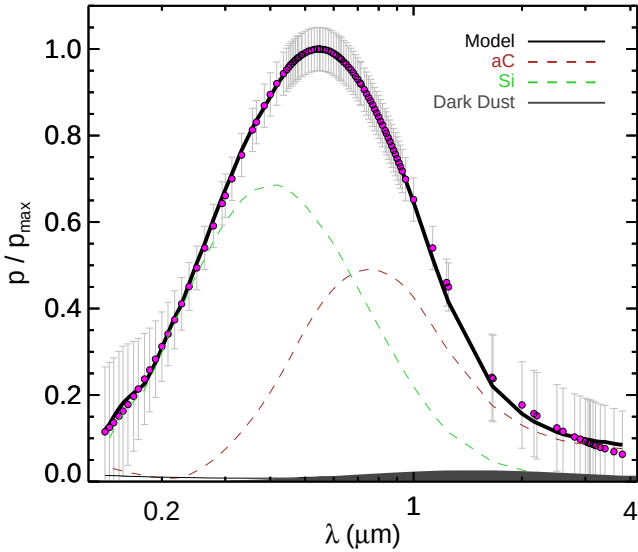


Fig. 3. Polarised extinction of the diffuse ISM (circles) with error bars indicating the observed scatter ([Voshchinnikov et al. 2012](#); [Bagnulo et al. 2017](#)). The model (black) with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ (Table 1) and contributions (dashed) from large amorphous carbon (brown), large silicate grains (green), and the dark dust area in grey, when treated as prolate particles is shown.

empirical formula given by [Serkowski et al. \(1975\)](#),

$$p(\lambda) = p_{\text{max}} \exp \left[-k_p \ln^2 \left(\frac{\lambda_{\text{max}}}{\lambda} \right) \right], \quad (7)$$

where λ_{max} is the wavelength at maximum polarisation p_{max} , and k_p is the width of the spectrum. Significant variations in the width $0.5 \lesssim k_p \lesssim 1.5$ towards different sightlines are observed, using HPOL⁷, the Wisconsin UV Photo-Polarimeter WUPPE satellites, and ground-based instruments as compiled

⁷ <http://www.sal.wisc.edu>

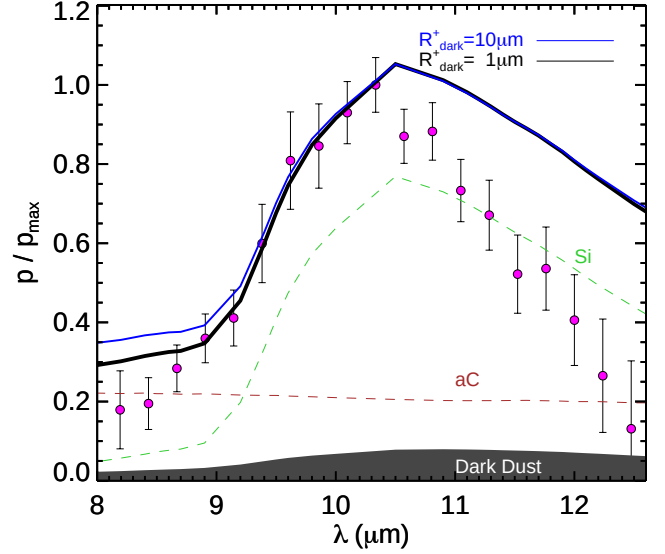


Fig. 4. Polarised extinction in the MIR. A composite spectrum (circles) of two Wolf-Rayet stars, WR 48A and AFGL 2104 by [Wright et al. \(2002\)](#), the model (full line) with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ (black) and contribution (dashed) from large amorphous carbon (brown), large silicate grains (green), and dark dust (grey) when treated as prolate particles, as well as the model with $r_{\text{Dark}}^+ = 10 \mu\text{m}$ (blue) is shown. Parameters are the same as in Table 1.

by [Efimov \(2009\)](#) and by the Large Interstellar Polarisation Survey ([Bagnulo et al. 2017](#)). Bagnulo and colleagues were unable to confirm the linear trend of $k_p \propto \lambda_{\text{max}}$ claimed in earlier work ([Wilking et al. 1980](#); [Whittet et al. 1992](#)). Observations of 160 sightlines of mildly reddened stars show that $p_V/E_{B-V} \lesssim 9\%/mag$ and $p_{\text{max}} \lesssim 10\%$ ([Voshchinnikov et al. 2016](#)). Starlight polarisation reaches a maximum in the V band at $\lambda_{\text{max}} = 0.545 \mu\text{m}$, and $k_p = 1.15$ was selected to represent the mean Serkowski curve that shows a typical scatter of 5% near p_{max} , 10% at $p/p_{\text{max}} \lesssim 0.4$, and in the NIR $\sim 15\%$. At $\lambda > 1.5 \mu\text{m}$, the polarisation spectrum smoothly matches a power law with an exponent of ~ 1.6 ([Martin et al. 1992](#)). The fit naturally breaks in the MIR near the silicate band. The typical wavelength dependence of the observed polarised extinction is shown in the optical/NIR in Fig. 3 and in the MIR in Fig. 4.

A mean MIR-polarised extinction spectrum that covered the silicate band was constructed by [Wright et al. \(2002\)](#) by averaging observations of two Wolf-Rayet stars, WR 48A and AFGL 2104. The analysis by Wright shows that the polarised extinction of silicates with stoichiometry and optical constants (n, k) of $\text{Mg}_{0.4}\text{Fe}_{0.6}\text{SiO}_3$, MgFeSiO_3 , as well as MgFeSiO_4 provides a pure fit, whereas $\text{Mg}_{0.8}\text{Fe}_{1.2}\text{SiO}_4$ give an almost perfect fit to the polarisation spectrum ([Wright et al. 2002](#)). The molecular weight of these materials varies between $\mu = 97\text{--}141$. This uncertainty directly affects the estimates of the gas-to-dust mass ratio. The silicate composition observed towards the Wolf-Rayet stars is distinct from $\text{Mg}_{1.3}(\text{Fe}, \text{Ni})_{0.3}\text{SiO}_{3.6}$ that is adopted for the diffuse ISM ([Draine & Hensley 2021a](#)). There are marked differences between the environments of the dust-producing circumstellar shells of the bright Wolf-Rayet stars and the diffuse ISM. Towards both sightlines, the stellar reddening is higher by a factor ~ 3 than what is typical for the diffuse ISM, and indications of ice absorption at $6.1 \mu\text{m}$ are found ([Marchenko & Moffat 2017](#)). Therefore, the silicate composition of the diffuse ISM was retained. Nevertheless, the analysis exemplifies

that a characterisation of the silicate stoichiometry and particle shape by MIR spectro-polarisation is viable. Unfortunately, these observations were recorded in the last century (Smith et al. 2000), and novel high-sensitive instrumentation is needed to detect polarised MIR extinction in the diffuse ISM.

The polarised dust emission spectrum in the submm was observed by Planck Collaboration XVII (2014); Planck Collaboration XII (2020). If the polarised emission in the submm and the polarised extinction in the optical is due to the same grains, then this ratio in principle includes information on the grain elongation (Krügel 2003). For the ratio of 850 μm to V-band polarisation, a characteristic value of

$$\tau_V \frac{p_{850\mu\text{m}}}{p_V} = 4.31 \quad (8)$$

was adopted by Hensley & Draine (2021). In the diffuse ISM, variations for different sightlines are noted in the hydrogen column density N_H , $E(B - V)$, R_V , and hence τ_V (Eq. (6)).

3. Model

3.1. Dust populations

A dust model for the diffuse ISM is presented that agrees with present observational constraints: the [C]/[Si] abundance ratio (Eq. (1)), the spectral variation of the reddening, the starlight polarisation, the diffuse Galactic emission, and the polarised dust emission (Sect. 1). Two main grain materials were considered: amorphous silicates, and carbon. Dust particles need to be of different sizes to fit the reddening and polarisation curves. A power-law size distribution $dn(r)/dr \propto r^{-q}$ (Mathis et al. 1977) that ranges from the molecular domain ($r_- \sim 5 \text{ \AA}$) to a rather unconstrained upper size limit of several microns ($r_+ \lesssim 10 \mu\text{m}$) was applied. Three different dust populations are distinguished:

1. Nanoparticles with sizes smaller than 6 nm, which are in the form of very small silicates (vSi), very small graphite (VSG), and PAHs. Two types of PAH were treated, small molecules having 30 C and 12 H atoms, and clusters with 200 C and 40 H atoms. The cross sections of the nanoparticles and PAHs were taken from Siebenmorgen et al. (2014).
2. Large grains with radii between 6 and 350 nm, which are partly aligned and of prolate shape with an axial ratio $a/b = 2$. Large grains are made of amorphous silicates (Si) and amorphous carbon (aC). Scattering, absorption, and polarisation cross sections of spheroids were computed with the procedure outlined in Sect. 3.3.
3. Dark dust was included as a new additional grain component of micrometer-sized particles. Dark dust grains are taken to be some kind of fluffy aggregates that are made up of porous composites of large silicate and large amorphous carbon grains that loosely stick together.

Frosting of molecules on dark dust can be envisioned as an attractive reservoir of the reported O depletion, but was not considered because a detection of ice absorption bands in the diffuse ISM is lacking. Dark dust particles were treated as spheres unless otherwise stated. Only approximate methods are available to calculate the cross sections of fluffy grains. The numerical simple tool by Krügel & Siebenmorgen (1994) was used with the Bruggemann mixing rule. An averaged complex dielectric function, $\epsilon = m^2$ was computed by solving

$$\sum_i f_i \frac{\epsilon_i - \epsilon_{av}}{\epsilon_i + 2\epsilon_{av}} = 0 \quad \text{with} \quad \sum_i f_i = 1, \quad (9)$$

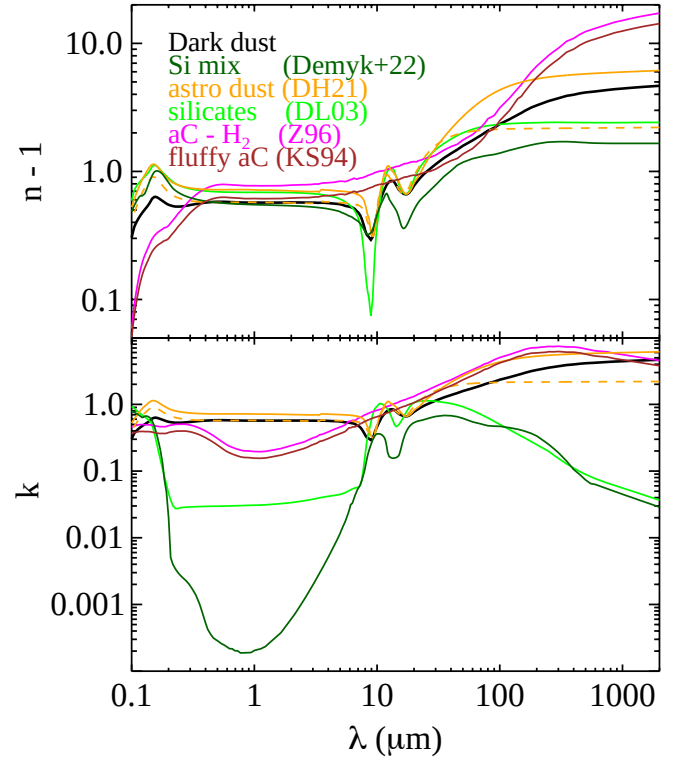


Fig. 5. Optical constants $n - 1$ (top) and k (bottom) for various grain materials.

where the volume fraction of each component i is denoted by f_i . The considered inclusions in a dark dust particle were silicates with $f_{\text{Si}} = 0.5$, amorphous carbon $f_{\text{aC}} = 0.3$, and vacuum with $f_{\text{vac}} = 0.2$ to represent porosity, while ices were ignored.

3.2. Porosity

The optical constants $m = n - ik$ with $k \geq 0$ of various grain materials are displayed in Fig. 5. Optical constants were shown for the aC-H₂ mixture of amorphous carbon by Zubko et al. (1996), graphite and silicate (Draine 2003; Draine & Hensley 2021a), and a 97:3 mix in mass of amorphous silicate grains with 2% vacuum inclusion that are composed of MgO–0.5 SiO₂ and Mg_{0.8}Fe_{0.2}²⁺ SiO₃ using optical constants by Demyk et al. (2022) and as discussed in Sect. 6. The Si and aC grains differ largely in n and k , respectively.

When fluffy particles with 20% porosity are considered, the optical constants are shifted to lower values and follow a similar spectral shape as for pure materials that do not have vacuum inclusions. This is shown in Fig. 5 by comparing aC-H₂ grains by Zubko et al. (1996) in magenta with fluffy aC (Krügel & Siebenmorgen 1994) with 20% vacuum inclusion and using Eq. (9) in brown. The spectral shape of the agglomerates by Draine & Hensley (2021a) is shown in Fig. 5 in orange without (full line) and with 20% porosity (dashed), which can be compared with fluffy composites in black. The latter are a representation of dark dust. In the latter two sets, similarities in the spectral shape of n and k are again visible, as is a larger shift in the far-IR (FIR) and mm where differences in the slope become more pronounced. When the vacuum content of materials is changed, the spectral slope remains unaltered. Thus the slope of the dust emissivity of a material, for example in the submm, does not change with porosity. For the same mass, the strength of the dust emissivity increases by increasing the

porosity because fluffy grains are larger than particles of the same material that have fewer or no vacuum inclusions.

3.3. Aligned spheroidal grains

The interstellar polarisation phenomenon in the optical and IR/mm cannot be explained by spherical dust particles. Interstellar polarisation of starlight and polarised dust emission is explained by partially aligned non-spherical dust grains that wobble and rotate about the axis of the greatest moment of inertia. Most simple representations of finite-sized non-spherical grains are spheroids. They are characterised by the ratio a/b between the major and minor semi-axes. Spheroids can either be in form of oblates, such as pancakes, or prolates, such as needles. The volume of a prolate is the same as that of a sphere with a radius given by $r^3 = a \cdot b^2$.

The dust optical depth at frequency ν is given by the product of the column density N_d of the dust along the sightline and the dust extinction cross section $C_{\text{ext}} = C_{\text{abs}} + C_{\text{sca}}$, which is the sum of absorption and scattering,

$$\tau(\nu) = N_d C_{\text{ext}}(\nu). \quad (10)$$

Linear polarisation is

$$p(\nu) = N_d C_p(\nu), \quad (11)$$

where C_p is the linear polarisation cross section.

Physical processes that led to grain alignment are currently discussed, and various mechanisms have been proposed; see the reviews by Voshchinnikov (2012) and Andersson et al. (2015). In the picket fence (Dyck & Beichman 1974), a fraction of the grains is perfectly aligned, while the other particles are randomly oriented. A modified version of this was used by Draine & Hensley (2021a), who assumed that the cross sections along the **E** and **B** field depends on $\cos^2 \theta$ of the scattering angle (the angle between the wave vector **k** of the incoming light and the symmetry axis of the grain). Non-magnetic alignment processes exist as well, for example in gas streams of stellar winds or in an-isotropic illumination, where photons are predominantly absorbed from one side of the particle. Radiative torque alignment has also become popular. In the Milky Way, the direction of the dust-induced polarisation in the optical is well correlated with the orientation of the magnetic field, which is derived from synchrotron emission in the radio. Hence magnetic fields are often taken to cause the grain alignment in the ISM. In this picture, questions arise when the relaxation times for the magnetic alignment of the grain are estimated in comparison to the time when disorder is again established through collisions with gas atoms. To solve this puzzle, supra-thermal grain rotation (at a frequency of 10^5 Hz) was proposed, as well as (super-)paramagnetic or ferromagnetic relaxation. In the following, the imperfect Davies-Greenstein mechanism (IDG) is applied, in which Fe atoms in the dust interact with the weak **B** field of the ISM. One advantage of IDG is that the orientation of a spinning and wobbling spheroid can be described mathematically in closed form. For angles ψ , φ , the precision angle β , and the magnetic field direction Ω , applied as in the notation by Hong & Greenberg (1980), and for the suffix TM for the transverse magnetic and TE for transverse electric polarisation direction as in the notation by Bohren & Huffman (1983), the alignment function becomes

$$f(\beta) = \frac{\frac{r+0.1 \delta_0}{r+\delta_0} \sin \beta}{\left(\left(\frac{r+0.1 \delta_0}{r+\delta_0} \right)^2 \cos^2 \beta + \sin^2 \beta \right)^{3/2}}. \quad (12)$$

The alignment efficiency $\delta_0 \sim 0.1\text{--}10 \mu\text{m}$ (Das et al. 2010; Siebenmorgen et al. 2014) is related to the physical picture. It impacts the maximum of the polarisation p_{max} but not the shape $p(\lambda)$ of the polarisation (Voshchinnikov & Das 2008). The cross sections were computed for given efficiency factors Q (Sect. 4.1) as the average over the orientation of the wobbling particles,

$$C_{\text{ext}}(\nu) = \frac{2}{\pi} \int (Q_{\text{ext}}^{\text{TM}} + Q_{\text{ext}}^{\text{TE}}) r^2 f(\beta) d\varphi d\Omega d\beta, \quad (13)$$

$$C_p(\nu) = \frac{1}{\pi} \int (Q_{\text{ext}}^{\text{TM}} - Q_{\text{ext}}^{\text{TE}}) r^2 f(\beta) \cos(2\psi) d\varphi d\Omega d\beta. \quad (14)$$

3.4. Reddening

The mass extinction cross sections $K_{\text{ext},i}(r)$, ($\text{cm}^2 \text{g}^{-1}\text{-dust}$) of a dust particle of population $i \in \{\text{Si}, \text{aC}, \text{vSi}, \text{VSG}, \text{Dark}\}$, radius r , and density ρ_i is

$$K_{\text{ext},i}(r) = \frac{m_i}{\frac{4\pi}{3} \rho_i} \frac{r^{-q}}{\int_{r_{-i}}^{r_{+i}} r^{3-q} dr} C_{\text{ext},i}(r). \quad (15)$$

The cross sections C were derived using efficiency factors Q , which are computed for spheres by Mie theory and spheroids as in Sect. 3.3. The relative weight, also called specific mass, in 1 g of dust in component i , is

$$m_i = \frac{\frac{[X]}{[H]}_i \mu_X}{\left(\frac{[C]}{[H]}_{\text{aC}} + \frac{[C]}{[H]}_{\text{gr}} + \frac{[C]}{[H]}_{\text{PAH}} \right) \mu_C + \left(\frac{[\text{Si}]}{[H]}_{\text{Si}} + \frac{[\text{Si}]}{[H]}_{\text{SSi}} \right) \mu_{\text{Si}}}, \quad (16)$$

where the relative dust abundances of an element X, which is either C or Si, with respect to H are denoted by $[X]/[H]_i$ together with the subscript i for each of the dust population, $\mu_C = 12$ is the molecular weight of carbon, and $\mu_{\text{Si}} = 134.46$ is that of silicate grains with bulk densities $\rho_C \sim 1.6 \text{ g cm}^{-3}$ and $\rho_{\text{Si}} \sim 3.41 \text{ g cm}^{-3}$ (Draine & Hensley 2021a). The specific mass for PAHs is computed in similar terms (Siebenmorgen et al. 2014). Specifying the mass extinction cross section per gram of dust has the advantage that only relative element abundances $[X]/[H]_i$ need to be specified instead of the more uncertain absolute solid-phase element abundances (in ppm), which may be used as a guideline, however. The total mass extinction cross section averaged over the dust size distribution in $\text{cm}^2/\text{g-dust}$ is

$$K_{\text{ext}} = \sum_i \int_{r_{-i}}^{r_{+i}} K_{\text{ext},i}(r) dr. \quad (17)$$

The wavelength dependence in the above expressions (Eqs. (13)–(17)) is dropped for clarity. The reddening curve of the dust model is derived using Eqs. (5) and (6) and noting K as the mass extinction cross section,

$$E(\lambda) = \frac{K_V}{K_B - K_V} \left(\frac{K(\lambda)}{K_V} - 1 \right). \quad (18)$$

When R_V (Eq. (5)) is used, the reddening $E(\lambda)$ is derived self-consistently from the dust model, without extrapolation to infinite wavelengths.

3.5. Emission

The emission $\epsilon_{v,i}(r)$ of a dust particle of radius r and grain material i at frequency ν is

$$\epsilon_{v,i}(r) = K_{v,i}^{\text{abs}}(r) \int P_i(r, T) B_\nu(T) dT, \quad (19)$$

where $K_{v,i}^{\text{abs}}$ is the mass absorption cross section (Eq. (15)), $B_\nu(T)$ is the Planck function, and $P_i(r, T)$ is the temperature distribution function that gives the probability of finding a particle of material i and radius r at temperature T . This function is determined from the energy balance between the emission and absorption of photons from the mean intensity J_ν , for which the ISRF by Mathis et al. (1983) is applied,

$$\int K_{v,i}^{\text{abs}}(r) J_\nu(T) d\nu = \int K_{v,i}^{\text{abs}}(r) P_i(r, T) B_\nu(T) dT d\nu. \quad (20)$$

It was evaluated using an iterative scheme that is described by Krügel (2008). The $P(T)$ function only needs to be evaluated for small grains as it approaches a δ -function for large particles where the temperature fluctuates very little around the equilibrium temperature. The total emission ϵ_ν of the dust at frequency ν is given as the sum of the emission $\epsilon_{v,i}(r)$ of all dust components.

3.6. Gas-to-dust mass ratio

Observations of the diffuse emission of the Galaxy are given per hydrogen column density, $\lambda I_\lambda/N_H$ (erg/s/sr/H-atom), whereas the dust emission of the model is computed (Eq. (19)) per dust mass (erg/s/sr/g-dust). For the necessary conversion of the dust to the gas column densities, a procedure is often applied that assumes that for sightlines in the diffuse ISM the extinction is proportional to the hydrogen column density $A_V = 1.086 \times \tau_V \propto N_H$. In addition, it is assumed that A_V can be reasonably estimated by applying a mean value of the total-to-selective extinction and the derived reddening using $A_V = R_V \times E(B - V)$. Furthermore, the ratio $\zeta = N_H/E(B - V)$ is assumed to stay roughly constant in the ISM. Traditionally, $\zeta = 5.8$ (10^{21} H cm $^{-2}$ mag $^{-1}$) is applied, which was derived from 75 sightlines observed within 3.4 kpc by Copernicus (Bohlin et al. 1978). For translucent clouds at $\tau_V \gtrsim 0.5$ observed by FUSE $\zeta = 5.94 \pm 0.37$, from here onwards in units as before (Rachford et al. 2009), and from X-ray observations $\zeta \sim 6.3$ – 6.5 (Zhu et al. 2017) using $R_V = 3.1$. However, striking differences were derived from radio observations of HI with lower values in earlier work of $\zeta = 4.6$ (Mirabel & Gergely 1979) and 5.1 (Knapp & Kerr 1974) or higher values in recent studies of $\zeta = 8.3$ (Liszt 2014), 8.8 (Lenz et al. 2017), and 9.4 (Nguyen et al. 2018). Dust emission of the diffuse ISM is observed towards high Galactic latitudes where there is less dust per H atom than in the Galactic plane, so that the latter value of ζ was favoured by Hensley & Draine (2021).

In the procedure applied here, these uncertainties in ζ , R_V , and $E(B - V)$ are avoided. A gas-to-dust mass ratio $M_{\text{gas}}/M_{\text{dust}}$ was introduced that is given by scaling the dust emission spectrum of Eq. (19) to the Planck data at $350 \mu\text{m}$. The observed emission was fit by

$$\frac{\lambda I_\lambda}{N_H} = \frac{M_{\text{dust}}}{M_{\text{gas}}} \frac{\lambda \epsilon_\lambda}{m_p}, \quad (21)$$

with H-atom mass m_p . The procedure has the advantage that $M_{\text{gas}}/M_{\text{dust}}$ is derived in the same direction as the direction in

which the data were taken. Uncertainties that arise due to possible variations in the strength of the ISRF towards the observed fields remain and are assumed to be small.

3.7. Polarised extinction

Starlight polarisation is derived by dichroic extinction of the dust (Eqs. (10)–(11), (14)),

$$p(\nu)/\tau_V = K_p(\nu)/K_{\text{ext},V}, \quad (22)$$

K_p denotes the total linear mass polarisation cross section (cm 2 /g-dust) and was computed similar to K_{ext} by replacing in Eq. (15) the cross section $C_{\text{ext},i}$ (Eq. (13)) with $C_{p,i}$ (Eq. (14)).

3.8. Polarised emission

The polarised dust emission of component i was computed by integrating over the minimum $r_{\text{pol},i}^-$ to maximum $r_{\text{pol},i}^+$ alignment radii,

$$\epsilon_{\text{pol},i}(\nu) = \int_{r_{\text{pol},i}^-}^{r_{\text{pol},i}^+} K_{\text{pol},i}(\nu, r) B_\nu(T) dr. \quad (23)$$

Note that $C_p = K_p = 0$ for spherical or non-aligned grains. The total polarised dust emission ϵ_{pol} is given as the sum of the polarised emission $\epsilon_{\text{pol},i}$ of all components contributing to the polarisation. These are large aC and Si prolate grains and dark dust when it is also considered of prolate shape. Polarisation by nanoparticles was not considered.

4. Method

The dust model was compared with the observational constraints presented in Sect. 2. As described by Zubko et al. (2004), the fitting procedure leads to a typical ill-posed inversion problem in which the solution is extremely sensitive to small changes in input data and with several priors such as the size distribution or grain composition as unknowns. Therefore, a least χ^2 -technique was applied for which first, a method for finding the best-fit of the reddening curve is presented that respects dust abundance constraints (Eq. (1)). For this model, the parameters that impact the shape of the starlight polarisation were varied to find the best-fit to the mean Serkowski curve. This model was then compared to the diffuse Galactic emission, which requires applying a gas-to-dust mass ratio. The flatness in the submm and mm polarisation spectrum as well as the ratio of the starlight polarisation to submm polarisation were tested. The parameter space of the model was explored, and the goodness of the fit was quantified as the sum of differences between observations and the model, each squared and divided by the observed data. For the reddening curve, the goodness parameter is denoted by χ_r^2 and for the polarised extinction, it is denoted χ_p^2 .

4.1. Cross sections

The various dust cross sections for extinction, scattering, and polarisation were computed in the spectral range between $90 \text{ nm} \lesssim \lambda \lesssim 1 \text{ cm}$ and for grain radius ranges between $5 \text{ \AA} \lesssim r \lesssim 10 \mu\text{m}$. The challenge was to compute the efficiency factors $Q = C/\pi r^2$ for the two polarisation directions of elongated particles (Eqs. (13) and (14)). For a small size parameter $x = 2\pi r/\lambda \ll 1$, the Rayleigh approximation might be used (Krügel 2008). For

typical ISM grains with sizes $r \leq 0.3 \mu\text{m}$, scattering becomes small at $\lambda \gtrsim 8 \mu\text{m}$, and the Rayleigh limit $2\pi r \ll \lambda$ is held. The Rayleigh approximation breaks at $x \gtrsim 0.25$ (Voshchinnikov 2004; Draine & Hensley 2021b) and cannot be used in most of the interesting cases. Electromagnetic absorption and scattering by spheroids can be treated using different methods. A numerical solution of separation of variables in the Maxwell equation was presented by Voshchinnikov & Farafonov (1993). The discrete dipole approximation by Draine & Flatau (1994) offers a possibility for the treatment of various grain structures. In addition, the extended boundary condition method by Mishchenko (2000), also known as T-matrix approximation, is available. The methods have been tested extensively by the authors, and excellent agreement at $x \sim 10$ was exemplified (Draine & Hensley 2021b). The program⁸ by Voshchinnikov & Farafonov (1993) was used. For a given complex optical constant m and the size parameter x , it returns the efficiency factors $Q_{\text{ext}}^{\text{TM}}(x, m)$ and $Q_{\text{ext}}^{\text{TE}}(x, m)$, (Eqs. (13) and (14)). The code converges up to $|m - 1| x \lesssim 25$, which is found to be at larger x than in most of the other applications.

4.2. Fitting procedure

The radial grid in grain size ascends using $r_{i+1} = 1.05 r_i$. Intermediate radii between two consecutive grid points were linearly interpolated when necessary. The upper radius of the dark dust was varied for six values of $r_{\text{Dark}}^+ = 0, 0.5, 0.8, 1, 5$, and $10 \mu\text{m}$, where $r_{\text{Dark}}^+ = 0 \mu\text{m}$ refers to a model without dark dust. Models assuming even larger grains were also inspected, but no striking features were found. When a continuous distribution in the particle size is assumed, the minimum radius of the dark dust follows that of the maximum radius of the large aC and Si grains, hence $r_{\text{Dark}}^- = \max(r_{\text{ac}}^+, r_{\text{Si}}^+)$. Models fitting the observational constraints show $r_{\text{ac}}^+ < r_{\text{Si}}^+$. The exponent of the size distribution q was kept as a free parameter, but the same q was used for all three dust populations. After some experiments, the mass in dark dust was adopted to be 10% of the total dust mass; this parameter was fine-tuned when the dust emission in the mm range was fit. Dust abundances are given in the model in relative terms, and one parameter can be kept fixed, and $[\text{Si}]/[\text{H}]_{\text{Si}} = 15 \text{ ppm}$ was set.

The polarisation data were fit by large grains only unless otherwise specified. A detailed fit to the Serkowski curve was obtained when the alignment of both large grain materials aC and Si differ. Models fitting the absolute values of the polarisation were applied towards individual sightlines that are dominated by a single absorbing cloud (Siebenmorgen et al. 2018b). Hence parameters that change p_{max} but do not affect the spectral shape of the polarisation were held constant (Voshchinnikov 2012). This concerns the magnetic field direction, which was set to $\Omega = 60^\circ$, the ratio of the major to minor axis of prolates $a/b = 2$, and the alignment efficiency of aC grains $\delta_0(\text{aC}) = 10 \mu\text{m}$, while variations of Si grains of $\delta_0(\text{Si}) = 0.5, 1$, and $10 \mu\text{m}$ were explored. The maximum alignment radius r_{pol}^+ shows no strong variations in starlight polarisation spectrum, whereas the minimum alignment radius r_{pol}^+ has a strong impact (Siebenmorgen et al. 2014). As maximum alignment radius, the upper radius derived from the reddening fit was applied, $r_{\text{pol, Si}}^+ = r_{\text{Si}}^+$ and $r_{\text{pol, aC}}^+ = r_{\text{ac}}^+$. The minimum alignment radius was taken as a free parameter for aC and Si grains. The Si grains dominate the polarisation curve at shorter wavelengths, and generally, $r_{\text{pol, Si}}^- \lesssim r_{\text{pol, aC}}^-$ is hold.

The reddening curve was fit using the 3×6 values as above for δ_0 and r_{Dark}^+ , which have a minor impact on $E_{\text{mod}}(\lambda)$, and in addition, the seven parameters of the dust model, $[\text{C}]/[\text{H}]_{\text{aC}}$, $[\text{C}]/[\text{H}]_{\text{VSG}}$, $[\text{C}]/[\text{H}]_{\text{PAH}}$, $[\text{Si}]/[\text{H}]_{\text{Si}}$, q , r_{ac}^+ , and r_{Si}^+ . A set of best-fit parameters was computed by a least χ^2 -technique using the Levenberg–Marquardt algorithm as implemented in MPFIT⁹ (Markwardt 2009). The algorithm can find local minima. The challenge is to identify the global $\chi_r^2(r)$ minimum of the reddening curve fit. This minimum was derived by starting the algorithm using many different initial parameter values. As an initial guess, the mean dust parameters of ISM sightlines fit by Siebenmorgen et al. (2018b) were applied: $[\text{C}]/[\text{H}]_{\text{aC}} = 67$, $[\text{Si}]/[\text{H}]_{\text{Si}} = 5$, $[\text{C}]/[\text{H}]_{\text{VSG}} = 17$, $[\text{C}]/[\text{H}]_{\text{PAH}} = 10$ (ppm), and $q = 3$. In addition, one initial radius r_i was selected out of 14 different upper sizes of large aC and Si grains of the radial grid between $180 \lesssim r_i = r_{\text{ac}}^+ = r_{\text{Si}}^+ \lesssim 350$ (nm). This limit is based on an exploration of the model space, which has shown that start values of $r_i > 350$ nm did not result in acceptable solutions. An initial MPFIT run was started keeping $r_{\text{ac}}^+ = r_{\text{Si}}^+$ fixed and after converging the resulting five parameters $[\text{C}]/[\text{H}]_{\text{aC}}$, $[\text{C}]/[\text{H}]_{\text{VSG}}$, $[\text{C}]/[\text{H}]_{\text{PAH}}$, $[\text{C}]/[\text{H}]_{\text{Si}}$, and q are held constant, while MPFIT was re-started a second time with r_{ac}^+ and r_{Si}^+ set as free.

This procedure was iterated, generally twice, until χ_r^2 was not reduced further. Then the starlight polarisation curve was fit by minimizing $\chi_p^2(\delta_0(\text{Si}), r_{\text{pol}}^-(\text{Si}), r_{\text{pol}}^-(\text{aC}))$ between the observed Serkowski curve (Eq. (7)) and the dust model (Eq. (22)). In this method, the seven best-fit dust parameters derived from the reddening curve procedure were held constant, and χ_p^2 was computed for the three $\delta_0(\text{Si})$ and all combinations of the minimum alignment radii of aC and Si grains between $6 \text{ nm} < r_{\text{pol}}^- < \min(r_{\text{ac}}^+, r_{\text{Si}}^+)$. To keep the computational time within reasonable limits, the fitting procedure was vectorized by running calls to MPFIT in which the many different start values were kept parallel.

5. Results

A $r_{\text{Dark}}^+ \times \delta_0(\text{Si}) \times r_{\text{ac}}^+$ tuple with $3 \times 6 \times 14$ models was computed by applying the procedure of Sect. 4.2. The model grid included the seven derived best-fit parameters to the reddening $[\text{C}]/[\text{H}]_{\text{aC}}$, $[\text{C}]/[\text{H}]_{\text{VSG}}$, $[\text{C}]/[\text{H}]_{\text{PAH}}$, $[\text{C}]/[\text{H}]_{\text{Si}}$, q , r_{ac}^+ , r_{Si}^+ , the two best-fit parameters to the starlight polarisation r_{ac}^+ , r_{Si}^+ , and the corresponding goodness parameters χ_r^2 and χ_p^2 for each combination of $\delta_0(\text{Si})$ and r_{Dark}^+ . Most models provide a reasonable fit to the reddening and polarisation curves, but do not respect the abundance constraint of $[\text{C}]/[\text{Si}] \lesssim 5.25$ (Eq. (1)) and were rejected. Out of the 252 models, 27 are consistent with the dust abundance ratio (Eq. (1)), and 22 remained after a 3σ outlier rejection in χ_r^2 and χ_p^2 was applied. Their χ_r^2 and χ_p^2 were each normalised to a mean of one, so that they could be combined. The model that simultaneously fit both curves best was selected from a minimum χ^2 condition in which each parameter was given the same weight using

$$\chi^2(r_{\text{Dark}}^+) = \frac{7}{10} \chi_r^2 + \frac{3}{10} \chi_p^2. \quad (24)$$

The model parameters with the minimum in $\chi^2 < 1$ for given r_{Dark}^+ are listed in Table 1. These models agree with the observed reddening and polarisation. Models that ignore dark dust ($r_{\text{Dark}}^+ = 0 \mu\text{m}$) underpredict the observed emission in the Planck

⁸ Fortran code SPVV8.5 kindly provided by N. Voshchinnikov[†].

⁹ <https://idlastro.gsfc.nasa.gov/ftp/pro/markwardt/mpfit.pro>

Table 1. Parameters of the dark dust model for the diffuse ISM using the [Draine \(2003\)](#) optical constants for amorphous silicate grains.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Model		Mass ratio (%) abundances (ppm)						Sizes					Derived quantities				
r_{Dark}^+ (μm)	χ^2 $N (\chi^2 < 1)$	m_{Dark}	m_{Si} $\frac{[\text{Si}]}{[\text{H}]}_{\text{Si}}$	m_{vSi} $\frac{[\text{Si}]}{[\text{H}]}_{\text{vSi}}$	m_{aC} $\frac{[\text{C}]}{[\text{H}]}_{\text{aC}}$	m_{VSG} $\frac{[\text{C}]}{[\text{H}]}_{\text{VSG}}$	m_{PAH} $\frac{[\text{C}]}{[\text{H}]}_{\text{PAH}}$	q	r_{Si}^+ (nm)	r_{ac}^+ (nm)	$r_{\text{pol,Si}}^-$ (nm)	$r_{\text{pol,aC}}^-$ (nm)	$\delta_0(\text{Si})$ (μm)	$\frac{[\text{C}]}{[\text{Si}]}$	$\frac{M_{\text{gas}}}{M_{\text{dust}}}$	R_V	τ_V
0 ^(‡)	0.5 0	–	46 15	23 7	25 92	4 15	3 10	3.0	243	203	80	166	0.5	5.2	125	3.09	1.01
0.75 ^(†)	0.7 0	7	43 15	20 7	24 96	4 15	2 8	3.0	228	201	84	166	0.5	5.5	138	3.16	1.42
1	0.6 5	6	44 15	21 7	23 88	4 15	2 8	3.0	217	207	76	143	1.0	5.0	131	3.09	1.37
5	0.6 3	7	41 15	22 8	23 95	3 13	3 11	2.9	220	208	80	166	0.5	5.2	124	3.11	1.30
10	0.7 3	6	49 15	17 6	22 91	3 14	2 8	3.1	239	222	88	183	0.5	4.6	124	3.18	1.36

Notes. In Col. 1 the upper radius of the dark dust agglomerates r_{Dark}^+ is specified, in Col. 2 the goodness χ^2 of the best-fit model, and below the number N of models that are consistent with the observational constraints and fit the reddening and Serkowski curve at $\chi^2 < 1$. Corresponding parameters of the specific mass in percent per gram dust (Cols. 3–8) of dark dust as lower limit m_{Dark} , and for large silicates m_{Si} , nano-sized silicates m_{vSi} , large amorphous carbon m_{aC} , very small graphite m_{VSG} , and PAHs m_{PAH} . Below, in the second row of Cols. 4–8, exemplified dust abundances $[\text{X}]/[\text{H}]$ (ppm) are given by adopting $[\text{Si}]/[\text{H}] = 15$ ppm in large silicates. Column 9 gives the exponent of the dust size distribution q . The upper radius of large silicates r_{Si}^+ (Col. 10) and amorphous carbon r_{ac}^+ (Col. 11), their lower alignment radii $r_{\text{pol,Si}}^-$ and $r_{\text{pol,aC}}^-$ (Cols. 12 and 13), respectively, and the alignment efficiency (Col. 14) of large silicates $\delta_0(\text{Si})$ is given. Derived quantities of the dust models are given for the dust abundance ratio $[\text{C}]/[\text{Si}]$ (Col. 15), the gas-to-dust mass ratio $M_{\text{gas}}/M_{\text{dust}}$ (Col. 16), the total-to-selective extinction R_V (Eq. (5), Col. 17), and the optical depth (Col. 18) that matches the optical-to-submm polarisation ratio of $p_{850\mu\text{m}}/(p_V/\tau_V) = 4.31$ (Eq. (8)) by [Planck Collaboration XII \(2020\)](#). ^(†) The model violates the abundance constraint (Eq. (1)). ^(‡) Models without dark dust do not fit the [Planck Collaboration XXI \(2015\); Planck Collaboration XII \(2020\)](#) data at ≥ 0.8 mm.

bands at wavelength ≥ 0.8 mm (Fig. 6). No model with $r_{\text{Dark}}^+ = 0.5 \mu\text{m}$ fits reddening and polarisation at $\chi^2 \lesssim 1$.

For $r_{\text{Dark}}^+ = 0.75 \mu\text{m}$, there is only one such model. It has $\chi^2 = 0.7$ but $[\text{C}]/[\text{Si}] = 5.5$ (Table 1, Col. 15). Hence it violates the abundance constraint (Eq. (1)). Therefore, at $r_{\text{Dark}}^+ < 1 \mu\text{m}$ no model is consistent with the observations at $\chi^2 < 1$, and the number of these models is $N (\chi^2 < 1) = 0$ (Table 1, Col. 2).

Models that agree with the observing constraints consider micrometer-sized dark dust particles at $r_{\text{Dark}}^+ \gtrsim 1 \mu\text{m}$. The global minimum over all models is found for $r_{\text{Dark}}^+ = 1 \mu\text{m}$ at $\chi^2 = 0.6$. For this radius, there are five models at $\chi^2 < 1$. The best-fitting models of $r_{\text{Dark}}^+ = 5$ and $10 \mu\text{m}$ have similar χ^2 ($\lesssim 0.7$). Their fits to the observed reddening, polarisation, and dust emission have a similar quality as the best-fit $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model. For each of these radii, there are $N (\chi^2 < 1) = 3$ models that fit the reddening and polarisation at $\chi^2 < 1$ and fulfil the abundance constraint $[\text{C}]/[\text{Si}] < 5.25$ (Eq. (1)). The scatter in the individual parameters between the selected models is small (Table 1). The peak-to-peak variations in the abundances for a given dust population (Table 1, Cols. 3–8) and the particular size parameters stay well below 10% (Table 1, Cols. 10–13).

The fit of the $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model with parameters of Table 1 to the observed reddening and extinction is shown in Fig. 1. The individual dust components show the known behaviour of the

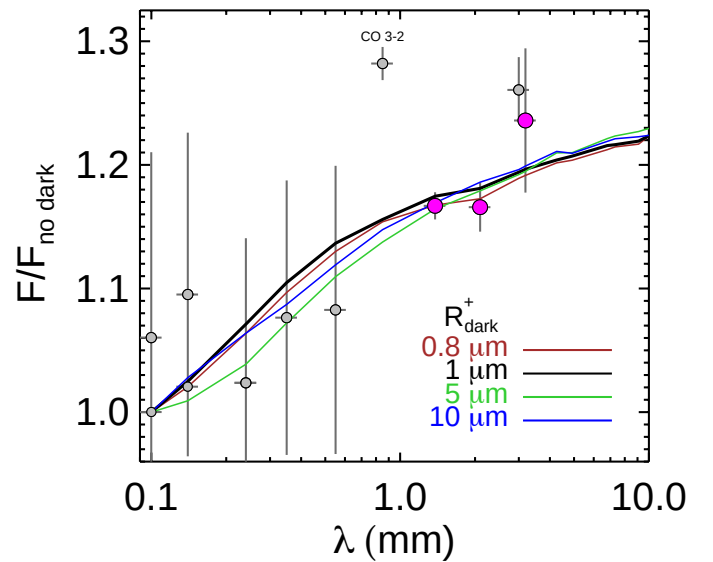


Fig. 6. Ratio $F/F_{\text{no dark}}$ of the dark dust models and the observed fluxes (circles, using the data of Fig. 2) divided by the model neglecting dark dust ($r_{\text{Dark}}^+ = 0 \mu\text{m}$). Best-fits (lines) to the 1.4 mm and 2.1 mm data were derived by varying the amount of dark dust m_{Dark} for models with $r_{\text{Dark}}^+ \gtrsim 0.75 \mu\text{m}$ as labelled. The parameters are the same as in Table 1.

reddening: nanoparticles cause the rise in the FUV, and PAH and VSG fit the 2175 Å extinction bump, large aC and Si grains give a rather flat contribution from the U band to shorter wavelengths. The constant reddening of dark dust from the FUV to the NIR is remarkable. It reaches wavelengths that are similar to the upper grain radius r_{Dark}^+ , which for this model lies at $\sim 1 \mu\text{m}$ (Fig. 1, right). The non-dispersed reddening provided by dark dust to the UBVRI bands is significant. Dark dust causes additional dimming of light that is not accounted for in dust models omitting this component.

The model fit to the observed starlight polarisation curve is shown in Fig. 3. To derive a detailed fit like this, it is necessary that both large Si and aC grains contribute to the polarisation and that both dust materials have distinct characteristics in the alignment radii and the polarisation efficiency (compare Cols. 10–14 of Table 1). Polarised extinction is dominated in the UV by Si grains and in the R band by aC grains. Dark dust treated as prolates with axial ratio $a/b = 2$, $\delta_o = 10 \mu\text{m}$, and $r_{\text{Dark}}^+ = 1 \mu\text{m}$ contributes most to p/p_{max} near $\sim 2 \mu\text{m}$ at less than a few percent.

Dark dust polarised extinction in the MIR is shown for models with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ and $r_{\text{Dark}}^+ = 10 \mu\text{m}$ in Fig. 4. Large aC grains show a flat polarisation at $\sim 20\%$ of the maximum MIR polarisation p_{max} , while Si grains dominate the spectrum. Dark dust, even when elongated and aligned, contributes to the normalised MIR polarisation by less than $p/p_{\text{max}} < 10\%$. The composite polarisation spectrum derived from observations of two Wolf-Rayet stars refers to greatly distinct environments from the diffuse ISM. Nevertheless, the data shown in Fig. 4 demonstrate the capabilities of using MIR polarisation as a method for estimating the stoichiometry of silicate grains.

The dust emission of the models was compared to the diffuse emission of the ISM that is observed at high Galactic latitudes, normalised per H atom, and is shown for the best-fit $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model in Fig. 2. The models are scaled to the 0.3 mm data, which allows for an estimate of the gas-to-mass ratio (Eq. (21)). A mean of $M_{\text{gas}}/M_{\text{dust}} = 126 \pm 4$ is derived for the best-fitting models (Table 1, Col. 16). The emission of the individual dust populations shows the known behaviour: nanoparticles and PAH dominate the MIR emission and large grains dominate the FIR/mm. The lowest temperature of aC grains is 16.8 K, the lowest temperature of Si grains is 14.8 K, and dark dust is as cold as 12.3 K for the $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model and 8.1 K for the $r_{\text{Dark}}^+ = 10 \mu\text{m}$. Dark dust emission peaks at $\sim 0.2 \text{ mm}$ and becomes a more important contributor in the mm range, where it even outshines the emission by large Si grains. This is expected from a comparison of the extinction cross sections of the different dust ingredients. Figure 7 shows the various PAH features and the 9.7 and $18 \mu\text{m}$ bands of the silicates, and it shows that aC grains dominate the cross sections over the entire spectrum at $\lambda \gtrsim 0.1 \mu\text{m}$, except near the $9.7 \mu\text{m}$ band. Furthermore, in the submm, the cross section of dark dust has a similar strength as Si grains. Dark dust shows a slightly shallower decline in the emissivity than the other grains in the mm range, which is as expected from the imaginary part k of the optical constants (Sect. 3.2).

Models that exclude dark dust, or models that do not alter the FIR/mm spectral index of the grain emissivity, do not account for the dust emission observed by Planck Collaboration XXI (2015); Planck Collaboration XII (2020). This is exemplified in Fig. 6. The observed flux F is divided by the flux $F_{\text{no dark}}$ of the models that do not consider dark dust ($r_{\text{Dark}}^+ = 0 \mu\text{m}$, Table 1). The latter is a kind of Siebenmorgen et al. (2014) model; they included non-porous prolate grains and fit the DIRBE and Planck data up to 0.35 mm. These models are at $F/F_{\text{no dark}} \sim 1$ in Fig. 6.

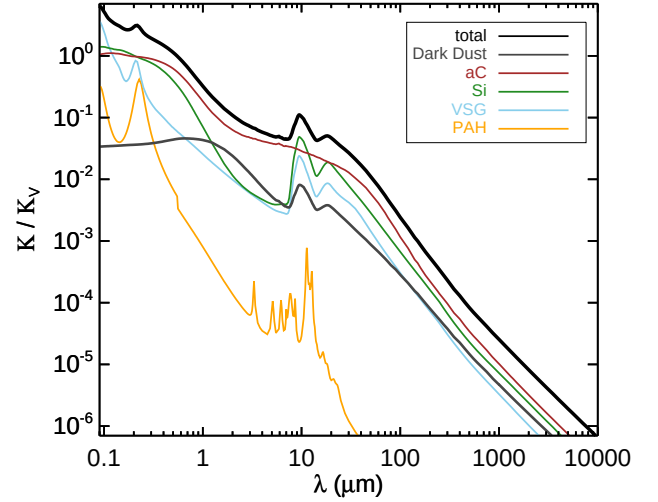


Fig. 7. Total extinction cross section normalized to V for the $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model (Table 1), with individual components as labelled.

They systematically underpredict the emission in the Planck bands at 0.8–3 mm by 15–30 %, which is significant considering the unprecedented precision of the Planck data. Fluffy and spheroidal grains show greater dust emissivity in the FIR/mm range than do non-porous and spherical grains of the same mass. The FIR/mm spectral slope of the dust emissivity stays invariable when the porosity or the axial ratio of the spheroidal particles are increased (compare Figs. 5 and 3 in Siebenmorgen et al. 2014). To fit the emission in the mm range, one must therefore either change the spectral index of the dust emissivity by a suitable set of optical constants (Draine & Hensley 2021a), or include dark dust.

The Planck bandpasses at 0.85 mm and 3 mm include dust and other emission components such as the CO (3–2) or CO (1–2) line transitions, and at longer wavelengths, free-free or synchrotron radiation (Galamez et al. 2014). The two least contaminated bandpasses near 1.4 mm and 2.1 mm were used to estimate a lower limit to the amount of dark dust. The mass of dark dust was varied in the $r_{\text{Dark}}^+ \gtrsim 0.75 \mu\text{m}$ models until a best-fit was found. Typically, the mass in dark dust is at least $m_{\text{Dark}} \gtrsim 6\%$ of the total dust mass (Table 1, Col. 3) to fit the Planck observed emission.

The polarised dust emission at $\lambda \gtrsim 0.85 \mu\text{m}$ was observed by Planck Collaboration XXI (2015); Planck Collaboration XII (2020) and between $0.25 \gtrsim \lambda \gtrsim 0.85 \mu\text{m}$ for selected areas on the sky by BLASTPol (Gandilo et al. 2016; Ashton et al. 2018; Shariff et al. 2019). The polarisation spectrum normalised to the fractional polarisation at 0.85 mm was tabulated by Hensley & Draine (2021) and is shown in Fig. 8. It features an astonishingly flat spectrum that is within 1σ of 11% constant and challenges several dust models (Draine & Hensley 2021a). The best-fit of the $r_{\text{Dark}}^+ = 1 \mu\text{m}$ dark dust model to the polarised emission spectrum is shown in Fig. 8 using the parameters of Table 1. The total fractional FIR/mm polarisation spectrum of the model is within $\sim 5\%$ constant, and aC grains are the dominating contributor over the Si grains.

Dark dust, when treated as prolate particles, and alignment efficiency as aC grains give a contribution of $\lesssim 10\%$ in the FIR and $\sim 35\%$ to the total polarisation in the mm range. The flatness of the submm/mm polarisation spectrum provides an upper limit of the total amount of dark dust. This is shown in Fig. 8, where the polarisation in the FIR is overestimated when the dark dust mass is increased to $m_{\text{Dark}} \gtrsim 12\%$ of the total dust mass.

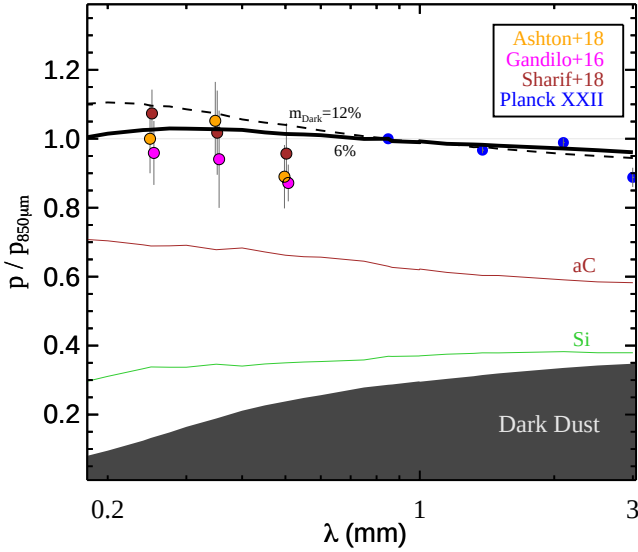


Fig. 8. Polarised emission of the diffuse ISM between 0.2 and 3 mm normalized to the polarisation at 850 μm . Observations (circles) with 1σ error bars are shown in blue by [Planck Collaboration XXI \(2015\)](#); [Planck Collaboration XII \(2020\)](#), in magenta by [Gandilo et al. \(2016\)](#), in brown by [Shariff et al. \(2019\)](#), and in orange by [Ashton et al. \(2018\)](#), as tabulated by [Hensley & Draine \(2021\)](#). The model with $r_{\text{Dark}}^+ = 1 \mu\text{m}$ (Table 1) and $m_{\text{Dark}} = 6\%$ of mass in dark dust (full line), the contributions from large amorphous carbon (brown) and large silicate grains (green), and the total polarisation fraction adopting $m_{\text{Dark}} = 12\%$ (dashed) is shown. The contribution from dark dust when it is treated as prolate particles is indicated by the area in grey.

The consistency of the models between optical and submm polarisation was verified. Polarised extinction and polarised emission are tightly connected when they are produced by the same grains. For the diffuse ISM, a characteristic value was provided by [Planck Collaboration XII \(2020\)](#), and it is given in Eq. (8). The dark dust models cope with this optical-to-submm polarisation ratio by adopting an optical depth of $1.3 \lesssim \tau_V \lesssim 1.37$ (Col. 18, Table 1). This is somewhat lower than derived for sightlines with translucent clouds by [Guillet et al. \(2018\)](#). These sightlines have a slightly higher reddening than the diffuse ISM. The optical depth was converted into dust reddening using the model-derived total-to-selective extinction R_V (Eq. (5)). The reddening of the models is $E(B - V) = \tau_V / 1.086 / R_V$ (Cols. 17 and 18 of Table 1) and ranges between 0.40 and 0.42 mag, which agrees well with the observationally derived mean of 0.45 mag ([Fitzpatrick & Massa 2007](#)).

6. Laboratory studies of cosmic dust analogues

Laboratory studies of cosmic dust analogues foster our knowledge in several research fields ([Jäger et al. 2020](#)): The experiments enlighten our understanding of processes leading to the formation or destruction of dust particles ([Jones et al. 1994](#)), the growth of grains to pebbles and planetesimals, and how dust eventually evolves into planets ([Wurm & Blum 1998](#); [Blum & Wurm 2008](#); [Wurm & Teiser 2021](#)). In the laboratory, chemical reaction paths of interstellar gas with charged or uncharged dust and nanoparticles and their interaction on the grain surfaces can be simulated ([Salama et al. 1996](#); [Herbst 2001](#); [Jones 2021](#)). Scattering matrices and phase functions of several irregular shaped particles have been measured ([Muñoz et al. 2020](#)).

Experimental results of optical constants for a range of dust materials were obtained, although they are limited in the

wavelength coverage ([Dorschner et al. 1995](#); [Mennella et al. 1998](#); [Jäger et al. 2003](#), see the Heidelberg-Jena-St. Petersburg database¹⁰). Models aiming to simultaneously explain the dust absorption and emission of polarised and unpolarised light require a consistent set of optical constants from the Lyman limit to about 1 cm, at least. In this wavelength range, optical constants derived from laboratory experiments are available for various carbon materials. These were incorporated in dust models; see [Zubko et al. \(2004\)](#) for a comprehensive study. For amorphous silicate grains, a complete set of laboratory-derived optical constants suited for dust modelling was not available until the work by [Demyk et al. \(2022\)](#). Commonly, and as used in Sect. 4.2, the semi-empirical set by [Draine \(2003\)](#) is applied. These optical constants are based on laboratory measurements in the UV/optical by [Huffman & Stapp \(1973\)](#), on observations in the NIR and MIR, and on some extrapolation by a power law to longer wavelengths ([Draine & Lee 1984](#)). The same extrapolation was used by [Jones et al. \(2017\)](#), who considered in the UV/optical range optical constants of amorphous silicate dust by [Scott & Duley \(1996\)](#) and added metallic Fe and FeS inclusions to reproduce NIR observations. The exponent of the power law was modified by [Draine & Hensley \(2021a\)](#) to accommodate the deficit submm/mm emission that was present in all of the previous dust models when compared with the observations by the *Planck* mission ([Ysard 2020](#)).

Recently, [Demyk et al. \(2022\)](#) calculated optical constants between 10^{-2} and $10^5 \mu\text{m}$ of four Mg-rich glassy silicate dust particles with stoichiometry from about enstatite to olivine and eight samples of Mg- and Fe-rich silicates with stoichiometry close to pyroxene. For the samples, the mass absorption coefficients were measured at temperatures between 10 and 300 K and between 5 and $\sim 1000 \mu\text{m}$ ([Demyk et al. 2017a,b](#)). The optical constants of the samples show a significant temperature dependence at temperatures above 30 K and wavelengths $\gtrsim 80 \mu\text{m}$. The dust absorption cross section at 300 K is increased by about one order of magnitude when compared to the sample measured at 30 K. This temperature dependence of the cross section has been neglected in dust models so far. It results in an overestimate of the derived dust masses that is important for environments in which dust is heated to such high temperatures ([Fanciullo et al. 2020](#)). The optical constants remain constant between 10 and 30 K. In the diffuse ISM of the Milky Way, the temperatures of large grains stay below ~ 20 K. [Demyk et al. \(2022\)](#) adopted the refractive indices as measured for similar kinds of amorphous silicate grains by [Dorschner et al. \(1995\)](#) and [Jäger et al. \(2003\)](#) in the wavelength range between 0.5 and $1 \mu\text{m}$. The extrapolation of the measurements to the entire wavelength range is a delicate issue. In addition to the numerical challenges, detailed knowledge of the sample is required, such as the bulk density of the materials, the grain shapes and structures, and the particle size distribution of the agglomerates. These parameters were derived by investigating images of the samples obtained by using transmission electron microscopy ([Demyk et al. 2022](#)). Samples labelled ‘E’ consist of submicron-sized particles with irregular shapes that are characterised by prolates with axial ratios of $a/b \sim 2$ and glassy silicate with $a/b \sim 1.5$. These axial ratios are used in the following.

The fitting procedure of Sect. 4.2 was applied to the dust models by replacing the optical constants of the large silicate grains with those by [Demyk et al. \(2022\)](#) measured at 10 K. The alignment efficiency of silicates was set to $\delta_0 = 1 \mu\text{m}$. First, the contribution of dark dust was neglected. The models that

¹⁰ <https://www2.mpi-a-hd.mpg.de/HJPD0C>

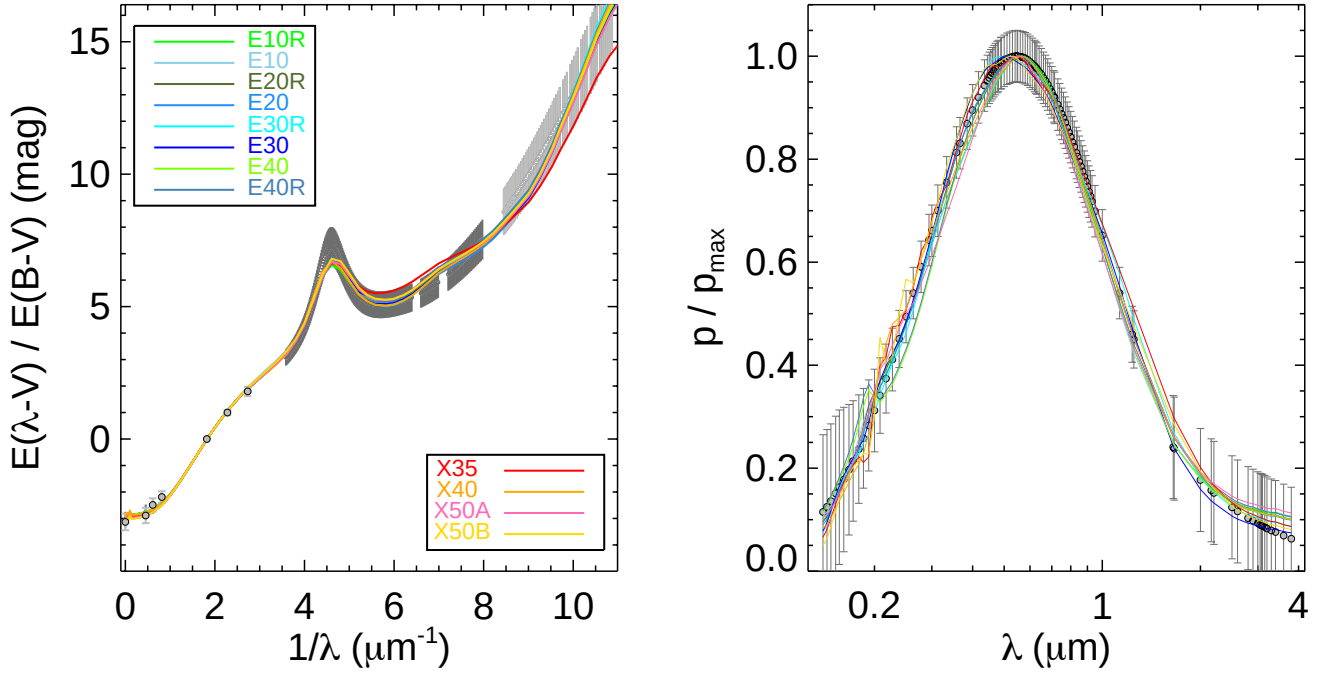


Fig. 9. Best-fits (full line) to the reddening (*left*) and starlight polarisation (*right*) using the [Demyk et al. \(2022\)](#) optical constants as labelled. The model parameters are the same as in Table 2, and the data are the same as in Figs. 1 and 3.

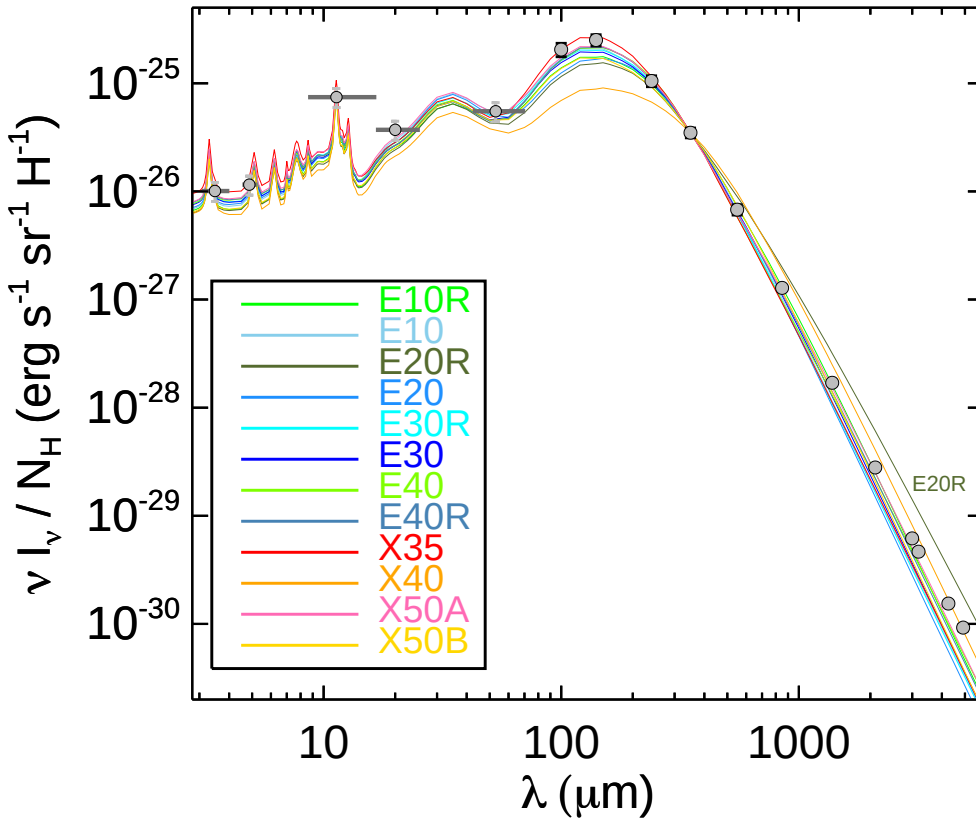


Fig. 10. Dust emission of the diffuse ISM for models using the [Demyk et al. \(2022\)](#) optical constants (as labelled) that simultaneously fit the reddening and starlight polarisation (Fig. 9). The model parameters are the same as in Table 2, and the data are the same as in Fig. 2.

are consistent with the abundance constraints (Eq. (1)) and that best-fit the reddening and starlight polarisation and the emission of polarised and unpolarised light simultaneously are shown in Figs. 9–11. The sample characteristics, dust parameters, and derived quantities of these models are summarised in Table 2. In this table, Cols. 1–4 provide the identifier, composition, molecular weight μ of the mean composition, and bulk density ρ

of the sample as given by [Demyk et al. \(2022\)](#). The parameters for the abundances of the dust populations (Cols. 4–8) and their size parameters (Cols. 9–13) are specified. The derived quantities such as the dust abundance ratio (Col. 15), the dust-to-gas mass ratio (Col. 16), the total-to-selective extinction (Col. 17), and the optical depth (Col. 18) that match the optical-to-submm polarisation ratio of $p_{850\mu\text{m}}/(p_V/\tau_V) = 4.31$ (Eq. (8)) by

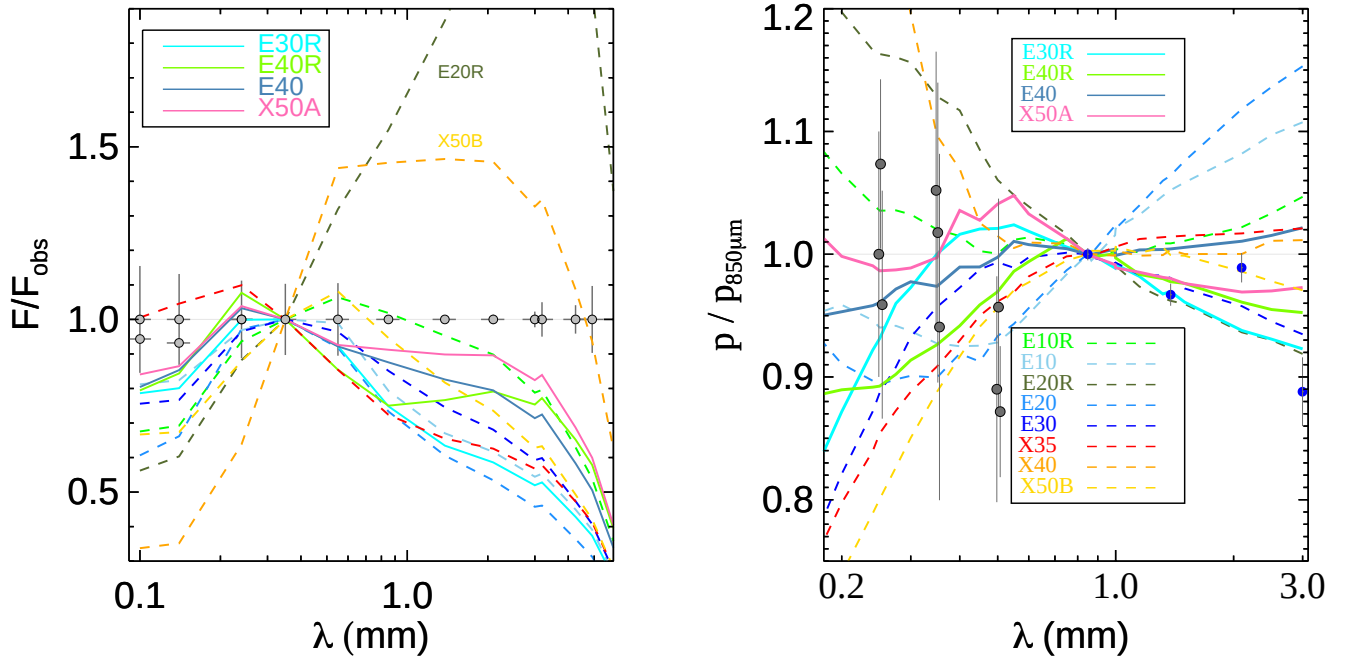


Fig. 11. Flux ratio of the observed photometry (*left*) and the polarised emission spectrum (*right*) with the data of Figs. 2 and 8, respectively. Models using the Demyk et al. (2022) optical constants (as labelled) that do not fit the polarised emission spectrum are shown by dashed lines and by a full line otherwise.

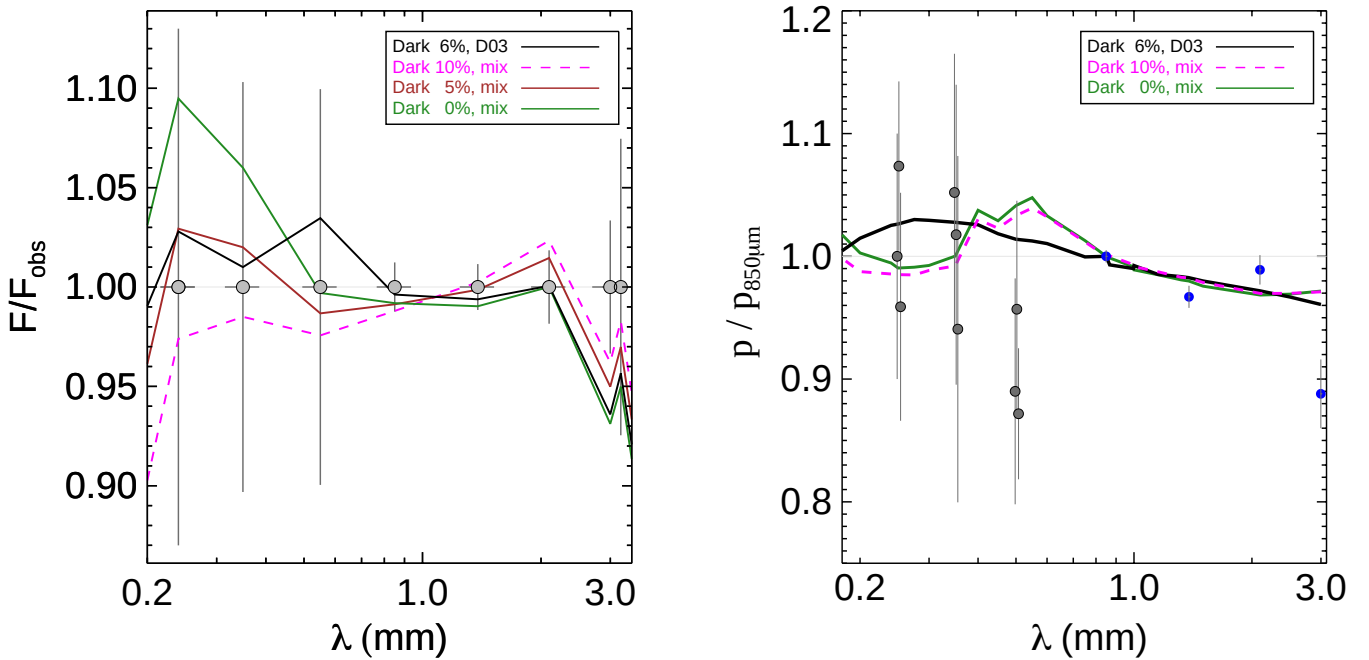


Fig. 12. As Fig. 11 for a 97:3 mix in mass of the $\text{MgO}-0.5 \text{ SiO}_2$ (X50A) and $\text{Mg}_{0.8}\text{Fe}_{0.2}^{2+} \text{ SiO}_3$ (E20R) of the Demyk et al. (2022) samples. The model with a contribution to the total dust mass of 0 (green), 5% (brown), and 10% (magenta) of dark dust is shown. The best-fit using the Draine (2003) optical constants and the parameters of Table 1 for the $r_{\text{Dark}}^+ = 1 \mu\text{m}$ model (black) is shown for comparison.

Planck Collaboration XII (2020). The goodness-of-fit parameter is given in Col. 14.

The mean reddening curve is fit reasonably well by all samples, except for sample X35, which overestimates the reddening between 5 and $7 \mu\text{m}^{-1}$ and underestimates the FUV rise (Fig. 9, left). The starlight polarisation spectrum is fit within the errors by all models (Fig. 9, right), although at somewhat larger dispersion than the dark dust model shown in Fig. 3.

However, none of these models fit the dust emission (Fig. 10). All models except for sample X35 underestimate the FIR emission and all models except samples E20R and X50B underestimate the emission $>0.5 \text{ mm}$ (Fig. 10). Thus estimates of the dust-to-gas mass ratios for these models shall be taken with caution. The model features of the dust emission become more apparent in the left panel of Fig. 11, where the ratio of the flux to the observed photometry is shown. Samples that do not fit

Table 2. Parameters of the dust model for the diffuse ISM using the Demyk et al. (2022) optical constants for amorphous silicate grains.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Sample		Abundances ^(†) $\frac{[X]}{[H]}$						Sizes				Derived quantities ^(‡)					
ID	Composition	μ (u)	ρ (g/cm^3)	vSi	aC	VSG (ppm)	PAH	q	r_{Si}^+	r_{ac}^+	$r_{pol, Si}^-$	$r_{pol, aC}^-$	χ^2	$\frac{[C]}{[Si]}$	$\frac{M_{gas}}{M_{dust}}$	R_V	τ_V
X35	0.65 MgO–0.35 SiO ₂	141	2.7	3	72	11	9	3.2	261	262	92	222	1.7	5.0	<115	–	–
X40	0.60 MgO–0.40 SiO ₂	121	2.7	4	29	7	8	2.9	286	261	72	88	0.5	2.4	<168	2.94	–
X50A	0.50 MgO–0.50 SiO ₂	100	2.7	3	57	10	6	3.0	267	248	54	72	0.8	4.0	<129	3.10	1.04
X50B	0.50 MgO–0.50 SiO ₂	100	2.7	4	63	11	7	3.0	257	251	102	233	0.8	4.3	<162	3.14	–
E10	Mg _{0.9} Fe _{0.1} ³⁺ SiO ₃	99.9	2.8	5	77	12	8	2.9	246	230	59	84	0.7	4.8	<148	3.08	–
E20	Mg _{0.8} Fe _{0.2} ³⁺ SiO ₃	99.3	2.9	3	41	10	6	3.0	266	253	72	97	0.7	3.1	<141	3.09	–
E30	Mg _{0.7} Fe _{0.3} ³⁺ SiO ₃	99.8	3.0	5	76	13	9	3.1	259	227	84	183	0.5	4.9	<165	2.99	–
E40	Mg _{0.6} Fe _{0.4} ³⁺ SiO ₃	99.3	3.1	5	75	12	9	3.1	235	252	57	92	0.6	4.9	<161	3.05	1.15
E10R	Mg _{0.9} Fe _{0.1} ²⁺ SiO ₃	99.9	2.8	4	64	10	8	3.0	257	238	66	92	0.7	4.2	<159	3.05	–
E20R	Mg _{0.8} Fe _{0.2} ²⁺ SiO ₃	99.3	2.9	3	46	9	6	3.0	267	260	69	92	0.7	3.3	<160	3.11	–
E30R	Mg _{0.7} Fe _{0.3} ²⁺ SiO ₃	99.8	3.0	6	85	13	10	3.0	235	234	88	192	0.5	5.2	<159	3.00	1.18
E40R	Mg _{0.6} Fe _{0.4} ²⁺ SiO ₃	99.3	3.1	5	73	13	8	3.2	237	244	59	102	0.6	4.8	<162	2.98	1.14

Notes. Notation as in Table 1. ^(†) The abundance of large amorphous silicate grains is $[Si]/[H] = 15$ ppm. ^(‡) Models that do not fit the reddening or polarised emission (Planck Collaboration XII 2020) are indicated by the long dash, and models that do not fit the dust emission (Dwek et al. 1997; Planck Collaboration XXI 2015) are indicated by the symbol ‘<’.

the observed polarised emission spectrum are indicated by a dashed line and those that do are shown by full lines, those are samples E30R, E40R, E40 and X40. The potpourri of the fits to the polarised emission spectrum is shown in the right panel of Fig. 11. Samples that do not fit the 0.25–0.5 mm polarisation spectrum by Gandilo et al. (2016), Shariff et al. (2019), and Ashton et al. (2018) within 15% or deviates by more than 5σ from the Planck Collaboration XII (2020) polarisation spectrum in the millimeter are indicated by dashed lines.

When the curves that are shown in the panels of Fig. 11 are mixed, a flattened curve arises that better fits the data. The sample X50A appears particularly attractive as it already fits the polarisation data and the FIR/submm emission up to 0.8 mm. This model only falls short in the mm region, and this deficit emission may be filled up using the sample E20R, which gravely overestimates the submm/mm emission. A 97:3 mix in mass of the MgO–0.5 SiO₂ (X50A) and Mg_{0.8}Fe_{0.2}²⁺ SiO₃ (E20R) provides a simultaneous fit to all the observing constraints. This dust mix without a contribution by dark dust is shown in Fig. 12, together with models that include dark dust contributing to 5% and 10% to the total dust mass, respectively. The best-fit using the Draine (2003) optical constants and parameters as in Table 1 for the $r_{Dark}^+ = 1 \mu m$ model is shown for comparison. All four models provide a similarly good fit to the data.

7. Conclusion

Dark dust was suggested for the unification of spectroscopic and parallax-derived distances. These grains have a wavelength-independent reddening, and non-selective extinction in the optical was already considered by Trumpler (1930). The extinction properties of these particles require that they are large. Their absorbed energy is re-emitted in the FIR-mm.

I included dark dust as an additional grain population to a dust model of the diffuse ISM. The model copes with the current state of observations and provides constraints on the physical properties of dust in the diffuse ISM. Major observations that were verified are representative solid-phase element abundances,

FUV-NIR reddening, optical-NIR polarised extinction, FIR-mm dust emission of polarised and unpolarised light, and the ratio of the optical-to-submm polarisation. A dust model with 11 parameters for the various grain abundances, sizes, and alignment properties accounts for these data simultaneously. The parameter space was explored by a vectorised iterative fitting procedure to derive the physical properties of dark dust. Different sets of optical constants for amorphous silicate grains were analysed. The principal findings of the study are listed below.

1. A large set of models that account for the mean reddening, extinction, and starlight polarisation curves of the Milky Way fails to respect the adopted abundance constraints.
2. A detailed fit to the Serkowski curve was derived assuming different alignment characteristics of large aC and Si grains.
3. Dark dust consists of micrometer-sized particles of at least $r_{Dark}^+ \gtrsim 1 \mu m$.
4. Dark dust provides a significant wavelength-independent reddening in the UV/optical and up to wavelengths $\lambda \lesssim r_{Dark}^+$.
5. In the FIR/mm, the extinction cross section of dark dust has similar strengths as Si grains and shows a slightly fainter slope than large grains.
6. The detected Planck excess emission at 0.8–3 mm that previous models were unable to explain without ad hoc changes in the slope of the dust emissivity or adjustments of the optical constants is provided by the emission of very cold (8–12 K) dark dust. Very cold dust is frequently observed in other non-active galaxies.
7. The observed flatness of the submm/mm polarisation spectrum is held by the model unless the mass in dark dust is $\lesssim 12\%$ of the total dust mass.
8. Dark dust, when treated as aligned prolate particles with $r_{Dark}^+ = 1 \mu m$, does not provide a significant contribution to the observed polarised extinction, polarisation in the 10 μm silicate band, and polarised emission at $\lambda \lesssim 1 mm$. At longer wavelengths (1–3 mm), dark dust may contribute to about one-third of the maximum polarisation.
9. Dark dust models fit the characteristic value of the optical-to-submm polarisation ratio assuming an optical depth of

$\tau_V = 1.25 \pm 0.13$. The total-to-selective extinction varies between $2.9 \lesssim R_V \lesssim 3.2$, which translates into a mean reddening of $E(B - V) \sim 0.4$ mag in the diffuse ISM.

10. The gas-to-dust mass ratio is $M_{\text{gas}}/M_{\text{dust}} = 126 \pm 4$ in the models using optical constants by [Draine \(2003\)](#). The estimate is consistent when a 97:3 mix is used in mass of silicate dust analogues to the samples by [Demyk et al. \(2022\)](#) of $\text{MgO}-0.5 \text{ SiO}_2$ and $\text{Mg}_{0.8}\text{Fe}_{0.2}^{2+}\text{SiO}_3$. This mixture provides a good fit to the observing constraints and still accommodates up to 5–10% of mass in dark dust.

Current spectro-polarisation in the MIR demonstrates the ability to constrain the stoichiometry of silicate grains. More sensitive MIR polarisation spectra are required along sightlines of the diffuse ISM to constrain the models presented here. Dark dust with icy grain mantles would foster grain growth and provide a reservoir for the as yet unaccounted O depletion. For the manifestation of such a model, ice absorption features in the diffuse ISM need to be detected. Observations will be possible with the high sensitivity of the JWST spectrometers.

The dark dust model will be applied to individual sightlines to explain the absolute reddening and polarisation towards selected stars. This requires a unification of distance estimates to the star either when derived by spectroscopy or from parallax. Dust models that ignore dark dust do not account for the unification of the two distance estimates. Dark dust causes significant dimming of light that is not treated in some contemporary research, for example by estimating spectroscopic distances and the calibration of supernova Ia light curves ([Phillips 1993](#); [Riess et al. 1996](#)). This deserves further investigation.

Acknowledgements. I am grateful to Karen Demyk for granting me early access to optical constants of the laboratory samples of amorphous silicate grains. I am grateful to Endrik Krügel and Rolf Chini for helpful discussions.

References

- Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, *ApJS*, **71**, 733
- Andersson, B. G., Lazarian, A., & Vaillancourt, J. E. 2015, *ARA&A*, **53**, 501
- Andriess, C. D., Donn, B. D., & Viotti, R. 1978, *MNRAS*, **185**, 771
- Ashton, P. C., Ade, P. A. R., Angilè, F. E., et al. 2018, *ApJ*, **857**, 10
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, **47**, 481
- Bagnulo, S., Cox, N. L. J., Cikota, A., et al. 2017, *A&A*, **608**, A146
- Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, *AJ*, **156**, 58
- Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, *AJ*, **161**, 147
- Blum, J., & Wurm, G. 2008, *ARA&A*, **46**, 21
- Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, *ApJ*, **224**, 132
- Bohren, C. F., & Huffman, D. R. 1983, *Absorption and Scattering of Light by Small Particles* (Hoboken: Wiley)
- Bowen, D. V., Jenkins, E. B., Tripp, T. M., et al. 2008, *ApJS*, **176**, 59
- Chen, X., Wang, S., Deng, L., & de Grijis, R. 2018, *ApJ*, **859**, 137
- Chini, R., Krügel, E., Haslam, C. G. T., et al. 1993, *A&A*, **272**, L5
- Chini, R., Hoffmeister, V. H., Nasser, A., Stahl, O., & Zinnecker, H. 2012, *MNRAS*, **424**, A195
- Compiègne, M., Verstraete, L., Jones, A., et al. 2011, *A&A*, **525**, A103
- Das, H. K., Voshchinnikov, N. V., & Il'in, V. B. 2010, *MNRAS*, **404**, 265
- Demyk, K., Meny, C., Leroux, H., et al. 2017a, *A&A*, **606**, A50
- Demyk, K., Meny, C., Lu, X. H., et al. 2017b, *A&A*, **600**, A123
- Demyk, K., Gromov, V., Meny, C., et al. 2022, *A&A*, **666**, A192
- Deng, D., Sun, Y., Wang, T., Wang, Y., & Jiang, B. 2022, *ApJ*, **935**, 175
- Desert, F. X., Boulanger, F., & Puget, J. L. 1990, *A&A*, **500**, 313
- Do-Duy, T., Wright, C. M., Fujiyoshi, T., et al. 2020, *MNRAS*, **493**, 4463
- Dorschner, J., Begemann, B., Henning, T., Jaeger, C., & Mutschke, H. 1995, *A&A*, **300**, 503
- Draine, B. T. 2003, *ApJ*, **598**, 1017
- Draine, B. T., & Flatau, P. J. 1994, *J. Opt. Soc. Am. A*, **11**, 1491
- Draine, B. T., & Friauf, A. A. 2009, *ApJ*, **696**, 1
- Draine, B. T., & Hensley, B. S. 2021a, *ApJ*, **909**, 94
- Draine, B. T., & Hensley, B. S. 2021b, *ApJ*, **919**, 65
- Draine, B. T., & Lee, H. M. 1984, *ApJ*, **285**, 89
- Dunkin, S. K., & Crawford, I. A. 1998, *MNRAS*, **298**, 275
- Dwek, E., Arendt, R. G., Fixsen, D. J., et al. 1997, *ApJ*, **475**, 565
- Dyck, H. M., & Beichman, C. A. 1974, *ApJ*, **194**, 57
- Efimov, Y. S. 2009, *Bull. Crimean Astrophys. Observ.*, **105**, 82
- Fanciullo, L., Guillet, V., Aniano, G., et al. 2015, *A&A*, **580**, A136
- Fanciullo, L., Kemper, F., Scicluna, P., Dharmawardena, T. E., & Srinivasan, S. 2020, *MNRAS*, **499**, 4666
- Fischera, J. 2004, *A&A*, **428**, 99
- Fitzpatrick, E. L., & Massa, D. 2007, *ApJ*, **663**, 320
- Fitzpatrick, E. L., Massa, D., Gordon, K. D., Bohlin, R., & Clayton, G. C. 2019, *ApJ*, **886**, 108
- Gaia Collaboration (Prusti, T., et al.) 2016, *A&A*, **595**, A1
- Gaia Collaboration (Brown, A. G. A., et al.) 2018, *A&A*, **616**, A1
- Gaia Collaboration (Brown, A. G. A., et al.) 2020, *A&A*, **650**, C3
- Galametz, M., Madden, S., Galliano, F., et al. 2009, *A&A*, **508**, 645
- Galametz, M., Albrecht, M., Kennicutt, R., et al. 2014, *MNRAS*, **439**, 2542
- Galliano, F., Madden, S. C., Jones, A. P., Wilson, C. D., & Bernard, J. P. 2005, *A&A*, **434**, 867
- Gandilo, N. N., Ade, P. A. R., Angilè, F. E., et al. 2016, *ApJ*, **824**, 84
- Gordon, K. D., Cartledge, S., & Clayton, G. C. 2009, *ApJ*, **705**, 1320
- Greenberg, J. M., Li, A., Mendoza-Gomez, C. X., et al. 1995, *ApJ*, **455**, L177
- Grenier, I. A., Casandjian, J.-M., & Terrier, R. 2005, *Science*, **307**, 1292
- Guillet, V., Fanciullo, L., Verstraete, L., et al. 2018, *A&A*, **610**, A16
- Hage, J. I., & Greenberg, J. M. 1990, *ApJ*, **361**, 251
- Heinz, S., Corrales, L., Smith, R., et al. 2016, *ApJ*, **825**, 15
- Henning, T. 2010, *Ann. Rev. Astron. Astrophys.*, **48**, 21
- Hensley, B. S., & Draine, B. T. 2021, *ApJ*, **906**, 73
- Herbst, E. 2001, in *Spectroscopy from Space*, eds. J. Demaison, K. Sarka, & E. A. Cohen (Berlin: Springer), 1
- Hong, S. S., & Greenberg, J. M. 1980, *A&A*, **88**, 194
- Huffman, D. R., & Stapp, J. L. 1973, in *Interstellar Dust and Related Topics*, eds. J. M. Greenberg, & H. C. van de Hulst (Berlin: Springer), 52, 297
- Indebetouw, R., Mathis, J. S., Babler, B. L., et al. 2005, *ApJ*, **619**, 931
- Jäger, C., Dorschner, J., Mutschke, H., Posch, T., & Henning, T. 2003, *A&A*, **408**, 193
- Jäger, C., Potapov, A., Rouillé, G., & Henning, T. 2020, *IAU Symp.*, **350**, 27
- Jenkins, E. B. 2009, *ApJ*, **700**, 1299
- Jones, B. F. 1972, *ApJ*, **171**, L57
- Jones, A. P. 2021, ArXiv e-prints [arXiv:2111.04516]
- Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1994, *ApJ*, **433**, 797
- Jones, A. P., Fanciullo, L., Köhler, M., et al. 2013, *A&A*, **558**, A62
- Jones, A. P., Köhler, M., Ysard, N., Bocchio, M., & Verstraete, L. 2017, *A&A*, **602**, A46
- Jura, M., Webb, R. A., & Kahane, C. 2001, *ApJ*, **550**, L71
- Kataoka, A., Tsukagoshi, T., Pohl, A., et al. 2017, *ApJ*, **844**, L5
- Kennicutt, R. C., Calzetti, D., Aniano, G., et al. 2011, *PASP*, **123**, 1347
- Kessler, M. F., Steinz, J. A., Anderegg, M. E., et al. 1996, *A&A*, **315**, L27
- Knapp, G. R., & Kerr, F. J. 1974, *A&A*, **35**, 361
- Köhler, M., Ysard, N., & Jones, A. P. 2015, *A&A*, **579**, A15
- Królowski, J., Galazutdinov, G. A., Strobel, A., & Mulas, G. 2016, *Acta Astron.*, **66**, 469
- Krügel, E. 2003, *The Physics of Interstellar Dust* (Bristol, UK: IOP Publishing)
- Krügel, E. 2008, *An Introduction to the Physics of Interstellar Dust* (Bristol, UK: IOP Publishing)
- Krügel, E., & Siebenmorgen, R. 1994, *A&A*, **288**, 929
- Krügel, E., Siebenmorgen, R., Zota, V., & Chini, R. 1998, *A&A*, **331**, L9
- Krüger, H., Strub, P., Grün, E., & Sterken, V. J. 2015, *ApJ*, **812**, 139
- Landgraf, M., Baggaley, W. J., Grün, E., Krüger, H., & Linkert, G. 2000, *J. Geophys. Res.*, **105**, 10343
- Lanz, T., Heap, S. R., & Hubeny, I. 1995, *ApJ*, **447**, L41
- Lenz, D., Hensley, B. S., & Doré, O. 2017, *ApJ*, **846**, 38
- Liszt, H. 2014, *ApJ*, **780**, 10
- Madden, S. C., Rémy-Ruyer, A., Galametz, M., et al. 2013, *PASP*, **125**, 600
- Maercker, M., Khouri, T., Mecina, M., & De Beck, E. 2022, *A&A*, **663**, A64
- Maíz Apellániz, J., & Barbá, R. H. 2018, *A&A*, **613**, A9
- Maíz-Apellániz, J., Walborn, N. R., Galué, H. Á., & Wei, L. H. 2004, *ApJS*, **151**, 103
- Marchenko, S. V., & Moffat, A. F. J. 2017, *MNRAS*, **468**, 2416
- Markova, N., Puls, J., Scuderi, S., Simón-Díaz, S., & Herrero, A. 2011, *A&A*, **530**, A11
- Markwardt, C. B. 2009, *ASP Conf. Ser.*, **411**, 251
- Martin, P. G., Adamson, A. J., Whittet, D. C. B., et al. 1992, *ApJ*, **392**, 691
- Martins, F. 2018, *A&A*, **616**, A135
- Mathis, J. S., & Whiffen, G. 1989, *ApJ*, **341**, 808
- Mathis, J. S., Rimpl, W., & Nordsieck, K. H. 1977, *ApJ*, **217**, 425
- Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, *A&A*, **500**, 259
- Mennella, V., Brucato, J. R., Colangeli, L., et al. 1998, *ApJ*, **496**, 1058

- Mennella, V., Baratta, G. A., Esposito, A., Ferini, G., & Pendleton, Y. J. 2003, *ApJ*, **587**, 727
- Mirabel, I. F., & Gergely, T. E. 1979, *A&A*, **77**, 110
- Mishchenko, M. I. 2000, *Appl. Opt.*, **39**, 1026
- Muñoz, O., Moreno, F., Gómez-Martín, J. C., et al. 2020, *ApJS*, **247**, 19
- Mulas, G., Zonca, A., Casu, S., & Cecchi-Pestellini, C. 2013, *ApJS*, **207**, 7
- Nguyen, H., Dawson, J. R., Miville-Deschênes, M. A., et al. 2018, *ApJ*, **862**, 49
- Nieva, M. F., & Przybilla, N. 2012, *A&A*, **539**, A143
- Ossenkopf, V. 1991, *A&A*, **251**, 210
- Pecaut, M. J., & Mamajek, E. E. 2013, *ApJS*, **208**, 9
- Phillips, M. M. 1993, *ApJ*, **413**, L105
- Planck Collaboration XII. 2020, *A&A*, **641**, A12
- Planck Collaboration XVII. 2014, *A&A*, **566**, A55
- Planck Collaboration XXI. 2015, *A&A*, **576**, A106
- Potapov, A., Bouwman, J., Jäger, C., & Henning, T. 2021, *Nat. Astron.*, **5**, 78
- Rachford, B. L., Snow, T. P., Destree, J. D., et al. 2009, *ApJS*, **180**, 125
- Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2013, *A&A*, **557**, A95
- Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, *ApJ*, **473**, 88
- Salama, F., Bakes, E. L. O., Allamandola, L. J., & Tielens, A. G. G. M. 1996, *ApJ*, **458**, 621
- Scicluna, P., Siebenmorgen, R., Wesson, R., et al. 2015, *A&A*, **584**, L10
- Scicluna, P., Kemper, F., McDonald, I., et al. 2022, *MNRAS*, **512**, 1091
- Scott, A., & Duley, W. W. 1996, *ApJS*, **105**, 401
- Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, *ApJ*, **196**, 261
- Shariff, J. A., Ade, P. A. R., Angilè, F. E., et al. 2019, *ApJ*, **872**, 197
- Shull, J. M., & Danforth, C. W. 2019, *ApJ*, **882**, 180
- Siebenmorgen, R., & Gredel, R. 1997, *ApJ*, **485**, 203
- Siebenmorgen, R., Krügel, E., & Chini, R. 1999, *A&A*, **351**, 495
- Siebenmorgen, R., Voshchinnikov, N. V., & Bagnulo, S. 2014, *A&A*, **561**, A82
- Siebenmorgen, R., Scicluna, P., & Krelowski, J. 2018a, *A&A*, **620**, A32
- Siebenmorgen, R., Voshchinnikov, N. V., Bagnulo, S., et al. 2018b, *A&A*, **611**, A5
- Siebenmorgen, R., Krelowski, J., Smoker, J., Galazutdinov, G., & Bagnulo, S. 2020, *A&A*, **641**, A35
- Siebenmorgen, R., Wright, C., Smoker, J., et al. 2022, *ECLA 2020* (Berlin: Spinger)
- Skórzyński, W., Strobel, A., & Galazutdinov, G. A. 2003, *A&A*, **408**, 297
- Smith, C. H., Wright, C. M., Aitken, D. K., Roche, P. F., & Hough, J. H. 2000, *MNRAS*, **312**, 327
- Sofia, U. J., & Meyer, D. M. 2001, *ApJ*, **558**, L147
- Sota, A., Maíz Apellániz, J., Walborn, N. R., et al. 2011, *ApJS*, **193**, 24
- Sota, A., Maíz Apellániz, J., Morrell, N. I., et al. 2014, *ApJS*, **211**, 10
- Spergel, D. N., Verde, L., Peiris, H. V., et al. 2003, *ApJS*, **148**, 175
- Stecher, T. P. 1965, *ApJ*, **142**, 1683
- Steinacker, J., Andersen, M., Thi, W. F., et al. 2015, *A&A*, **582**, A70
- Strom, K. M., Strom, S. E., & Yost, J. 1971, *ApJ*, **165**, 479
- Trumpler, R. J. 1930, *PASP*, **42**, 214
- Valencic, L. A., Clayton, G. C., & Gordon, K. D. 2004, *ApJ*, **616**, 912
- Voshchinnikov, N. V. 2004, *Astrophys. Space Phys. Res.*, **12**, 1
- Voshchinnikov, N. V. 2012, *J. Quant. Spec. Radiat. Transf.*, **113**, 2334
- Voshchinnikov, N. V., & Das, H. K. 2008, *J. Quant. Spectr. Rad. Transf.*, **109**, 1527
- Voshchinnikov, N. V., & Farafonov, V. G. 1993, *Ap&SS*, **204**, 19
- Voshchinnikov, N. V., & Henning, T. 2010, *A&A*, **517**, A45
- Voshchinnikov, N. V., Henning, T., Prokopenko, M. S., & Das, H. K. 2012, *A&A*, **541**, A52
- Voshchinnikov, N. V., Il'in, V. B., & Das, H. K. 2016, *MNRAS*, **462**, 2343
- Walborn, N. R. 1971, *ApJS*, **23**, 257
- Walborn, N. R., & Fitzpatrick, E. L. 1990, *PASP*, **102**, 379
- Wang, S., & Chen, X. 2019, *ApJ*, **877**, 116
- Weingartner, J. C., & Draine, B. T. 2001, *ApJ*, **548**, 296
- Westphal, A. J., Stroud, R. M., Bechtel, H. A., et al. 2014, *Science*, **345**, 786
- Whittet, D. C. B., Martin, P. G., Hough, J. H., et al. 1992, *ApJ*, **386**, 562
- Widmark, A., Korsmeier, M., & Linden, T. 2022, *ArXiv e-prints* [arXiv:2208.11704]
- Wilkink, B. A., Lebofsky, M. J., Martin, P. G., Rieke, G. H., & Kemp, J. C. 1980, *ApJ*, **235**, 905
- Witt, A. N., Smith, R. K., & Dwek, E. 2001, *ApJ*, **550**, L201
- Wright, C. M., Aitken, D. K., Smith, C. H., Roche, P. F., & Laureijs, R. J. 2002, in *The Origin of Stars and Planets: The VLT View*, eds. J. F. Alves, & M. J. McCaughrean (Berlin: Springer), 85
- Wurm, G., & Blum, J. 1998, *Icarus*, **132**, 125
- Wurm, G., & Teiser, J. 2021, *Nat. Rev. Phys.*, **3**, 405
- Ysard, N. 2020, *IAU Symp.*, **350**, 53
- Ysard, N., Köhler, M., Jones, A., et al. 2015, *A&A*, **577**, A110
- Zhu, H., Tian, W., Li, A., & Zhang, M. 2017, *MNRAS*, **471**, 3494
- Zhukovska, S., Henning, T., & Dobbs, C. 2018, *ApJ*, **857**, 94
- Zubko, V. G., Mennella, V., Colangeli, L., & Bussolletti, E. 1996, *MNRAS*, **282**, 1321
- Zubko, V., Dwek, E., & Arendt, R. G. 2004, *ApJS*, **152**, 211