Mid-infrared Extinction and Fresh Silicate Dust Toward the Galactic Center

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Abstract

We interpret the interstellar extinction observed toward the Galactic center (GC) in the wavelength range $\lambda = 1–20\ \mu m$. Its main feature is the flat extinction at 3–8 $\mu m$ whose explanation is still a problem for cosmic dust models. We search for the structure and chemical composition of dust grains that could explain the observed extinction. In contrast to earlier works, we use laboratory measured optical constants and consider particles of different structures. We show that a mixture of compact grains of aromatic carbon and of some silicate is better suited for reproducing the flat extinction in comparison with essentially porous grains or aliphatic carbon particles. Metallic iron should be located inside the particle, i.e., it cannot form layers on silicate grains as the extinction curves then become very peculiar. We find a model including aromatic carbonaceous particles and three-layered particles with an olivine-type silicate core, a thin, very porous layer and a thin envelope of magnetite that provides a good (but still not perfect) fit to the observational data. We suggest that such silicate dust should be fresh, i.e., recently formed in the atmospheres of late-type stars in the central region of the Galaxy. We assume that this region has a radius of about 1 kpc and produces about half of the observed extinction. The remaining part of extinction is caused by a “foreground” material being practically transparent at $\lambda = 4–8\ \mu m$.

Key words: dust, extinction – Galaxy: center – ISM: clouds

1. Introduction

The center parts of the Milky Way are a unique place to study different processes in the vicinity of a supermassive black hole, as well as dynamics and star formation under extreme conditions (Genzel et al. 2010; Mapelli & Gualandris 2016). The Galactic center (GC),

5 invisible at the optical wavelengths, can be observed in the infrared (IR), where the extinction amounts to $A_K = 2.349$ (Fritz et al. 2011). A distinguishing feature of GC extinction is its flat wavelength dependence at 3–5 $\mu m < \lambda < 8\ \mu m$. The flat or gray extinction in the GC was first measured by Lutz et al. (1996) with ISO, using hydrogen recombination lines, and confirmed by Lutz (1999), Nishiyama et al. (2009), and Fritz et al. (2011). Numerous recent observations appear to suggest the universality of flat extinction in the mid-IR for both diffuse and dense environments (see Wang et al. 2013 for a summary).

Fritz et al. (2011) compared different dust models capable of explaining the mid-IR extinction in the GC; these models include those from Weingartner & Draine (2001); mixture of carbonaceous and silicate spheres, Zubko et al. (2004); mixture of carbonaceous and silicate particles and additionally composite grains consisting of silicates, organic refractory material, water ice, and voids5; Dwek (2004); mixture of bare particles of Zubko et al. (2004) and additionally metallic needles, and Voshchinnikov et al. (2006; multi-layered spheres consisting of silicate, carbon, and vacuum). Wang et al. (2014) developed the idea of Dwek (2004) and additionally considered micrometer-sized particles from amorphous carbon, graphite, silicate, or iron. Such a model with amorphous carbon explained the flat extinction at 3–8 $\mu m$, but required a solid-phase C abundance C/H = 352 ppm that exceeded the solar abundance of carbon (269 ppm, Asplund et al. 2009). An important feature of the modelings mentioned above is the a priori selection of the optical constants of grain materials. Moreover, all of the authors used the optical constants of the “astronomical silicate” (astrosil) obtained by empirical fits to some observations by Draine & Lee (1984). The imaginary part of the complex refractive index of astrosil $k$ slightly grows with $\lambda$ in the region 3–8 $\mu m$, which does not coincide with the behavior of $k$ for any silicate material (see Figure A.1 in Jones et al. 2013).

It should be emphasized that there are no cosmic dust models that can explain the flat (excess) mid-IR extinction observed in the GC and other galactic objects. The COMP-AC-S model of Zubko et al. (2004) gives a good fit but produces a strong 3 $\mu m$ band, which disagrees with the trend found in the Coalsack nebula Globule 7 by Wang et al. (2013). The most recent model of Wang et al. (2015) includes 4 $\mu m$ clean water ice particles and explains both mid-IR extinction and the abundance of oxygen in dust, but the ice particles can hardly be so large and clean in the interstellar medium (ISM).

In this paper, we analyze a large set of dust models, concentrating on variations of grain structure and a proper presentation of grains’ chemical composition, to find a model that fits the near- and mid-IR extinctions and the 10 $\mu m$ feature observed to the GC. The next section contains a description of the observational data and the models. The results and their discussion are presented in Section 3. Concluding remarks are given in Section 4.

2. Observational Data and Dust Model

The GC extinction has been observationally obtained by Fritz et al. (2011; the region 1.3–19 $\mu m$), Nishiyama et al. (2009; 1.2–8 $\mu m$), and Chiar & Tielens (2006; 1.2–25 $\mu m$). The
latter paper contains the probable extinction profile of the 9.7 \( \mu m \) silicate feature for the GC. We have normalized all data in order to have \( A_{Ks} = 2.49 \) at \( \lambda_{Ks} = 2.17 \mu m \),

\[
A^*(\lambda) = \frac{A(\lambda)}{A_{Ks}} 2^{0.49},
\]

plotted in all figures below.

Note that the GC extinction was estimated from observations in different ways. As a result, the data of Fritz et al. (2011) are mainly derived for the central 14'' \( \times \) 20'' region, the data of Nishiyama et al. (2009) are averaged over the region \(|l| < 3^\circ, |b| < 1^\circ\), and the data of Chiar & Tielens (2006) are the extinction toward the Wolf–Rayet star WR 98a (\( l \approx 358^\circ, b \approx 0^\circ\)) extending the line of sight to GCS3. However, the extinction law for \( \lambda < 14 \mu m \) is practically the same. Hence, the data can be combined and the question of where the dust that produces the extinction is located is not as important as it could be.

We base our analysis on the model of Hirashita & Voshchinnikov (2014), who chose the initial size distributions of silicate and carbonaceous dust that fitted the mean Milky Way extinction curve with \( R_V = 3.1 \) (Weingartner & Draine 2001) and who considered dust grain size evolution due to the accretion and coagulation processes.

So, our model contains two populations of grains: silicate (Si) and carbonaceous (C),\(^7\) with the size distributions from Hirashita & Voshchinnikov (2014). As extinction only weakly depends on the particle shape (Voshchinnikov & Das 2008), we assume that dust grains are spherical.

Thus, the model has the following parameters: (1) the chemical composition of silicate and carbonaceous particles; (2) the structure of particles; (3) the relative number of silicate grains \( \kappa_{Si} = N_{Si} / N_{dust} \), where \( N_{Si} \) and \( N_{dust} \) are the column densities of silicate grains and all dust particles, respectively;

\(^7\) To reproduce the 2175 Å feature small graphite spheres were also involved (see, e.g., Das et al. 2010).
at 10 \( \mu m \) were taken from Chiar & Tielens (2006). Note that their data for the 18 \( \mu m \) band are less reliable and that many silicates have the bending bands in the range 16–23 \( \mu m \) (see Henning 2010). Therefore, we did not model the 18 \( \mu m \) band.

3.1. Homogeneous Particles

We considered a number of two- and three-component models with compact homogeneous grains. We started with the standard mixture of grains of artificial silicate, astroisol, and amorphous carbon ACBE_zu (model 1, see Table 2 and Figure 1). As expected, the wavelength dependence of extinction derived was steeper than that given by observations.
The next step was to find better models by variations of the laboratory optical constants. A comparison between the models with the aliphatic and aromatic carbon models (2, 3) showed that the near-IR (λ < 2 μm) and mid-IR extinction was much better reproduced by the model with aromatic carbon cell1000. So, we chose this material as the basic one in the subsequent modeling.

Note that the carbon materials cell400 and cell1000 we used differ in the degree of “graphitization” (Jäger et al. 1998). Therefore, for the former, in first approximation, the imaginary part of the refractive index k ~ λ⁻¹ for λ = 1–10 μm, while for the latter, k ~ const. (for graphite, n, k grow with λ). Obviously, such graphitization favors excess IR extinction.

Further, we examined different types of silicates: olivines and pyroxenes with different contents of Mg and Fe (models 3–8). As can be seen, olivines better explain the observations as the silicate peak produced by pyroxenes is shifted to λ = 9.0–9.4 μm (Table 2 and Figure 1). Though forsterite grains (model 5) well fit the observed mid-IR extinction, in this case, dust grains contain no iron, which is hardly probable according to contemporary understanding of cosmic dust origin and evolution. Our attempts to add iron or water ice as the third component into our silicate-carbonaceous mixture (models 10, 11) failed as mid-IR extinction always became steeper.

### 3.2. EMT–Mie Calculations and Core-mantle Particles

The physical conditions in which dust grains originate and grow should lead to formation of heterogeneous particles, in particular, porous. Two grain structures are generally expected: layered particles corresponding to subsequent accretion of different species, and an alternative—particles with small more or less randomly distributed inclusions. In the former case, the optical properties of heterogeneous particles are modeled with the Mie-like theory for layered particles (in particular, core–mantle), in the latter case by using homogeneous particles with the averaged dielectric functions (EMT–Mie calculations).

We present four models with porous silicate or carbonaceous particles (models 12, 13 and 18, 19) to illustrate that the...
porosity does not make the fitting much better in comparison with the compact grains, but leads to the shift and decrease of the silicate peak.

We have also considered the models with the refractive indexes constructed by Jones (2012), Jones et al. (2013), and Köhler et al. (2014; models 14–17). None of these models produces the flat mid-IR extinction with the worst fit to the data given by aliphatic carbon optEC_{18} (model 15). The models 20 and 21 with core-mantle grains give a good opportunity to test the hypotheses of Jones et al. (2013), who predicted that in the diffuse ISM large a-C:H grains are to be covered by an a-C 20 nm thick envelope and large Si grains by an a-C 5 nm thick envelope. As can be seen, in this case extinction is inconsistent with the observations of the flat mid-IR extinction in the GC.

Note that an increase of the thickness of the a-C mantles of silicate grains leads to an increase of the mid-IR extinction, as has been demonstrated in the work of Köhler et al. (2014), where they also analyzed the effect of “dirtiness” of silicates (due to absorbing inclusions of FeS). However, this increase is certainly not enough, while the thick a-C mantles begin to affect the silicate band strength (see their Figure 3).

### 3.3. Three-layered Particles

The use of multi-layered particles permits a more sophisticated treatment of the processes of grain growth and evolution. Specifically, it is possible to analyze the role of iron which is one of the major dust-forming elements (Jones 2000; Dwek 2016). The abundance of iron in the solid-phase of the ISM may reach 97%–99% of the cosmic abundance (Voshchinnikov & Henning 2010). Iron can be incorporated into dust grains in the form of oxides (FeO, Fe_2O_3, Fe_3O_4), (Mg/Fe)-silicates, sulfide (FeS), and metallic iron. The last two cases come from the contemporary theory of dust condensation in circumstellar environments. Gail & Sedlmayr (1999, 2014) note that Fe and FeS start to condense at temperatures well below the stability limits of silicates like forsterite and enstatite. This should lead to formation of layered particle. At low temperatures, the conversion of solid iron into iron oxides may occur (Gail & Sedlmayr 2014, p. 306).

Figure 2 shows the wavelength dependence of extinction for the models with three-layered particles including of olivine and vacuum. Iron is located in the particle core (model 22), intermediate layer (model 23), or outer layer (model 24). As seen, the presence of metallic iron at any place inside a particle, excluding its core, drastically changes extinction—iron totally screens the underlying layers and influences the optics of the overlying ones. As a result, one cannot properly reproduce either the position and shape of the observed silicate band (models 23, 24) or the slope of the wavelength dependence of IR extinction (models 22, 23).

However, iron can be oxidized or sulfidized, which opens a way to explain the observations. Figure 3 shows the extinction calculated for four models with olivine particles (olmg50) coated by a thin very porous layer and a thin (2–3 nm thick) envelope of iron oxide or iron sulfide. It is evident that the model 25 with magnetite agrees closely with the observational data. This model well reproduces near-IR extinction and the 10 μm peak and gives nearly as large mid-IR extinction as observed. The model also produces the visual extinction A_V/A_K = 15.2 which is close to the observed median value equal to 13.4 (Nataf et al. 2016).

Note that the replacement of olivine with pyroxene (model 29) leads to even a better coincidence with the observed extinction at λ = 5–9 μm but does not allow one to explain properly the near-IR extinction and the position of the silicate feature.

So, we see that the model 25 is practically the only way of successful fitting of the data, when keeping in mind available information on cosmic dust. Considering the model 25 with the particles from olivine olmg50 and amorphous carbon cell1000 as a prototype of possible dust models for the GC.

### 3.4. Foreground Extinction

In previous modeling we ignored the distribution of the extinction along the line of sight. However, the three-dimensional extinction map of the GC shows that about half of the extinction in the sightlines of Nishiyama et al. (2009) is reached in a distance of about 5 kpc from the Sun (see Figure 9 in Schultheis et al. 2014).

We assume different populations of dust grains in the foreground dusty complexes and in the central galactic region. Most likely, the dust producing the foreground extinction is processed, in particular, the silicate grains are covered by carbon (Jones et al. 2013). Such grains are properly described by the theoretical model 20 and give a very low relative extinction in the mid-IR (A(7.5 μm)/A_K ~ 0.1–0.2), see Figure 4 and Köhler et al. (2014). However, there exist several places in the Galaxy where low mid-IR extinction has been observed. In Figure 4 we plotted the average extinction for three molecular clouds obtained by Chapman et al. (2009). It is visible that model 20 agrees roughly with the measurements.

For the central galactic region, we applied model 25 with a freshly formed silicate dust. The total extinction for our “two-cloud” model was calculated as

\[ A^{*}_{\text{total}}(\lambda) = f A^{*}_{\text{foreg}}(\lambda) + (1 - f) A^{*}_{\text{backg}}(\lambda), \]

where \( f \) is the contribution of the foreground clouds to the total extinction. Currently the available data (see, e.g., Schultheis et al. 2014) do not allow one to estimate the value of \( f \) with a sufficient accuracy, therefore we just use 0.5 for simplicity.

Figure 4 and Table 2 show the extinction produced by the two-cloud model (\( f = 0.5 \)). Its agreement with the observational data is not perfect, but is good enough.

### 4. Concluding Remarks

According to modern ideas of cosmic dust evolution in the diffuse ISM, silicate grains should be covered by a significant envelope from amorphous carbon on a short timescale (Jones et al. 2013). Moreover, amorphous olivine MgFeSiO_4 (olmg50) is a possible mineral in dust grains forming in the atmospheres of late-type giants, but it is not believed to be the main material of silicate particles in the ISM (see, e.g., Jäger et al. 2003b). Therefore, we suggest that silicate dust in our model is “fresh,” i.e., recently formed in the atmospheres of the late-type stars in the GC. Our suggestion is rather natural as the GC is dominated by old stars.

Carbonaceous particles are more processed in comparison with silicate ones, which is determined by the lower efficiency of their destruction (Slavin et al. 2015). Intense radiation fields

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9 Note that a model based on combination of three regions with different extinction curves has been considered by Gao et al. (2015).
in the GC are favorable for the fast photo-dissociative aromatization of a-C(H) materials (Jones et al. 2013, 2014).

Obviously, the model we found does not fit the data perfectly and one cannot exclude other possible solutions to the problem of the flat mid-IR extinction toward the GC. However, we pay attention to the potential of our approach—to relate the solution with a specific structure and composition of dust grains relying the laboratory data on optical constants and contemporary ideas on cosmic dust grain evolution.

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