On the absorption properties of metallic needles

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ABSTRACT

Needle-like metallic particles have been suggested to explain a wide variety of astrophysical phenomena, ranging from the mid-infrared interstellar extinction to the thermalization of starlight to generate the cosmic microwave background. These suggestions rely on the amplitude and the wavelength dependence of the absorption cross sections of metallic needles. On the absence of an exact solution to the absorption properties of metallic needles, their absorption cross sections are often derived from the antenna approximation. However, it is shown here that the antenna approximation is not an appropriate representation since it violates the Kramers-Kronig relation. Stimulated by the recent discovery of iron whiskers in asteroid Itokawa and graphite whiskers in carbonaceous chondrites, we call for rigorous calculations of the absorption cross sections of metallic needle-like particles, presumably with the discrete dipole approximation. We also call for experimental studies of the formation and growth mechanisms of metallic needle-like particles as well as experimental measurements of the absorption cross sections of metallic needles of various aspect ratios over a wide wavelength range to bound theoretical calculations.

Key words: dust, extinction – infrared: ISM – intergalactic medium

1 INTRODUCTION

In the Galactic interstellar medium (ISM), typically 90% or more of the iron (Fe) element is missing from the gas phase (Jenkins 2009), suggesting that Fe is the largest elemental contributor to the interstellar dust mass after O and C and accounts for ∼25% of the dust mass in diffuse interstellar regions. However, as yet we know little about the nature of the Fe-containing material. Silicate grains provide a possible reservoir for the Fe in the form of interstellar pyroxene (Mg₂₃Fe₇₋ₓₐ₃₋ₙSi₄₋ₙO₁₃₋ₙ) or olivine (Mg₂Fe₂₋ₙ,SO₄₃₋ₙ) analogues. Nevertheless, the shape and strength of the 9.7 μm interstellar silicate feature in extinction suggest that the silicate material is Mg-rich rather than Fe-rich (Poteet et al. 2015) and therefore that a substantial fraction (∼70%) of the interstellar Fe is in other forms such as iron oxides (e.g., Fe₃O₄), iron sulfides, or metallic iron (see Draine & Hensley 2013, Hensley & Draine 2017, Westphal et al. 2019). Also, Fe abundances and depletions in the ISM often diverge from the pattern shown by Si and Mg, suggesting that Fe is not tied to the same grains as Si and Mg, and therefore that most silicate grains are likely Mg-based while Fe is probably incorporated into grain types such as metals or oxides.

As a matter of fact, small metallic particles were among the materials initially proposed to be responsible for the interstellar reddening (Schalén 1936, Greenstein 1938). About a half century later, the idea of metallic grains as an interstellar dust component was reconsidered by Chlewicki & Laureijs (1988) who argued that small iron particles with a typical size of ∼70 Å would obtain an equilibrium temperatures of ∼53 K in the Galactic cirrus diffuse ISM and account for the 60 μm emission measured by the Infrared Astronomical Satellite (IRAS) broadband photometry. Iron grains have long been neglected since it is commonly accepted that ∼2/3 of the IRAS 60 μm emission of the Galactic cirrus arises from stochastically heated nano-sized dust grains (Draine & Li 2001) and ∼1/3 of that arises from “classical”, submicron-sized grains which attain equilibrium temperatures in the ISM (Li & Draine 2001).

Thanks to the successful operations of the Infrared Space Observatory (ISO) and the Spitzer Space Telescope, numerous observations have shown that the mid infrared (IR) extinction at 3 μm < λ < 8 μm is flat or “gray” for both diffuse and dense environments (Lutz 1999, Indebetouw et al. 2005, Jiang et al. 2006, Flaherty et al. 2007, Gao et al. 2009, Nishiyama et al. 2009, Wang et al. 2013, Xue et al. 2016, Hensley & Draine 2020). The flat mid-IR extinct-
critical in assessing the role of needles in explaining a wide variety of astrophysical phenomena. Unfortunately, there exists no exact solution to the interaction of metallic needles with electromagnetic radiation. In the literature, their absorption properties are often derived either from needle-like spheroids under the Rayleigh approximation assumption (see Li 2003a and references therein) or from the antenna approximation (Wright 1982). However, we have shown in a previous paper (Li 2003a) that the Rayleigh approximation is invalid since the Rayleigh criterion is not satisfied for highly conducting needles. We will show in this work that the antenna approximation is not applicable either since it violates the Kramers-Kronig relation, a fundamental physical principle. We stress that our goal here is not to directly assess the role of metallic needles in explaining any specific astrophysical phenomenon, but rather to assess the applicability of the antenna approximation for calculating the absorption cross sections of metallic needles which serve as an essential ground for the former.

2 ANTENNA APPROXIMATION FOR METALLIC NEEDLES

Following Wright (1982), we consider a conducting needle-like dust particle represented by a circular cylindrical of radius \( a \), length \( l \) \((a \ll l)\), mass density \( \rho_m \), and mass \( m_{\text{dust}} = \pi a^2 l \rho_m \). Let \( \rho_R \) be its resistivity, \( R = \rho_R l / \pi a^2 \) be its resistance, and \( V \) be the voltage on the needle. If the resistance is the primary limit to current flow, then the power \( P \) absorbed in the grain is

\[
P = \frac{V^2}{R} = \frac{1}{3} \left( \frac{\lambda}{R} \right)^2 \frac{\pi a^2 E^2 l}{\rho_R},
\]

where \( E \) is the amplitude of the incident electric field, and the factor of \( 1/3 \) arises from averaging over the angles of incidence between the electric field and the needle (Wright 1982). The absorption cross section is given by

\[
C_{\text{abs}} = P/S = \frac{4\pi a^2}{3c} \frac{\rho_R}{\rho_{R,\nu}} \tag{2}
\]

where \( S = (c/4\pi) E^2 \) is the time-averaged Poynting vector of the incident radiation, and \( c \) is the speed of light. The long wavelength cutoff for \( C_{\text{abs}} \) will come when the capacitive reactance of the needle equals its resistance. This gives a long wavelength cutoff (see Wright 1982)

\[
\lambda_0 = \frac{1}{2} \frac{\rho_R c}{\rho_{R,\nu}} \left( \frac{1}{a} \right)^2 \ln \left( \frac{1}{a} \right). \tag{3}
\]

Therefore, the absorption cross section for a conducting metallic needle is given by

\[
C_{\text{abs}}(\lambda) = \frac{4\pi a^2}{3c} \frac{\rho_R}{\rho_{R,\nu}}, \quad \lambda \leq \lambda_0, \tag{4}
\]

\[
\frac{4\pi a^2}{3c} \frac{\rho_R}{\rho_{R,\nu}} (\lambda/\lambda_0)^{-2}, \quad \lambda > \lambda_0. \tag{5}
\]

3 CONSTRAINTS FROM THE KRAMERS-KRONIG RELATIONS

The antenna representation of the absorption cross sections for metallic needles (see eq. 4) is straightforward and easy
to compute. But it is unclear whether it is appropriate for extremely elongated conducting needles. In this section, we will test this approximation in terms of the Kramers-Kronig relations.

Let \( C_{\text{ext}}(\lambda) \) be the extinction cross sections of a conducting needle-like particle at wavelength \( \lambda \), and \( \int_0^\infty C_{\text{ext}}(\lambda)d\lambda \) be the extinction integrated over the entire wavelength range from 0 to \( \infty \). As shown by Purcell (1969), the Kramers-Kronig dispersion relations can be used to relate \( \int_0^\infty C_{\text{ext}}(\lambda)d\lambda \) to the grain volume \( V_{\text{dust}} \) through

\[
\int_0^\infty C_{\text{ext}}(\lambda)d\lambda = 3\pi^2 V_{\text{dust}} F(\varepsilon_0; \text{shape}) ,
\]

where \( F \) is the orientationally-averaged polarizability relative to the polarizability of an equal-volume sphere (Purcell 1969). The dimensionless factor \( F \) depends only upon the grain shape and the static (zero-frequency) dielectric constant \( \varepsilon_0 \) of the grain material (Purcell 1969, Draine 2003, Li 2003b). For prolates of axial ratio \( l/a \), where \( l \) is the semiaxis along the symmetry axis, and \( a \) is the semiaxis perpendicular to the symmetry axis, \( F \) is given by

\[
F(\varepsilon_0; l/a) = \frac{\varepsilon_0 - 1}{9} \left[ \frac{1}{1 + L_{||} (\varepsilon_0 - 1)} + \frac{2}{1 + L_{\perp} (\varepsilon_0 - 1)} \right] ,
\]

where \( L_{||} \) and \( L_{\perp} \) are the depolarization factors parallel and perpendicular, respectively, to the grain symmetry axis and are given by

\[
L_{||} = \left( 1 - e^2 \right) \left( \frac{1}{2e} \ln \left( \frac{1 + e}{1 - e} \right) - 1 \right) ,
\]

\[
L_{\perp} = \frac{1 - L_{||}}{2} ,
\]

where the eccentricity \( e \) is

\[
e = \sqrt{1 - (a/l)^2} .
\]

The \( F \) factors for highly conducting (\( \varepsilon_0 \to \infty \)) prolates and oblates have been calculated in Li (2003b). For extremely elongated prolates (\( l \gg a \)), \( L_{\min} \approx (a/l)^2 \ln (l/a) \) and therefore \( F(\varepsilon_0; l/a) \approx (l/a)^2 / [9 \ln (l/a)] \) for highly conducting (\( \varepsilon_0 \to \infty \)) and extremely elongated prolates. We will take the \( F \) factor of metallic needles to be that of highly conducting, extremely elongated prolates.

For a given set of absorption cross sections as a function of wavelength, we can apply eq. 6 to obtain a lower bound on the needle mass \( m_{\text{dust}}^{\min} \). Since \( C_{\text{ext}} = (C_{\text{abs}} + C_{\text{sca}}) > C_{\text{abs}} > 0 \) (where \( C_{\text{abs}} \) and \( C_{\text{sca}} \) are the absorption and scattering cross sections, respectively; and both are positive numbers), the integration of \( C_{\text{abs}} \) over \( \lambda = 0 \) to \( \infty \) therefore represents a lower limit to \( \int_0^\infty C_{\text{ext}}(\lambda)d\lambda \), and implies a lower limit to the needle mass

\[
m_{\text{dust}}^{\min} = \frac{\rho_m}{3\pi^2 F(\varepsilon_0; l/a)} \int_0^\infty C_{\text{abs}}(\lambda)d\lambda = \frac{8\lambda_0 \rho_m \pi a^2 l}{9\pi c F \rho_R} ,
\]

where we have used eq. 4 the antenna representation of the absorption cross sections for conducting needles. Therefore, we can obtain the ratio of \( m_{\text{dust}}^{\min} \), a lower limit to the needle mass, to \( m_{\text{dust}} \), the actual needle mass,

\[
\frac{m_{\text{dust}}^{\min}}{m_{\text{dust}}} = \frac{8\lambda_0}{9\pi c F \rho_R} = \frac{4}{9\pi F \ln (l/a)} .
\]

Since \( m_{\text{dust}}^{\min} < 1 \) for all physically reasonable systems. However, as shown in Figure 1 we find \( m_{\text{dust}}^{\min}/m_{\text{dust}} > 1 \) for needles of both small and large elongation \( l/a \) (the ra-
ratio of the length $l$ to the radius $a$), implying that the antenna approximation shown in eqs. [4] is not an appropriate representation for the absorption cross sections of metallic needles.

It is interesting to note that since $m_{\text{dust}}/m_{\text{dust}}$ is independent of the resistivity $\rho_{\text{R}}$ of the needle material (provided that the needle is made of conducting materials), our conclusion is applicable to any conducting needles, e.g., graphite whiskers, iron needles, nichrome (Ni-Cr) needles, and iron needles containing a small fraction of embedded impurities. It is also interesting to note that $m_{\text{dust}}/m_{\text{dust}}$ is independent of the circular cylindrical radius $a$; it depends only upon the elongation $l/a$, as long as the needle is highly conducting so that $\varepsilon_0 \to \infty$.

4 DISCUSSION

Metallic iron particles are expected to condense in circumstellar shells irrespective of the O/C ratio (Gilman 1969; Grossman 1972; Lewis & Ney 1979; Kozasa & Hasegawa 1988). In O-rich stars, Gail & Sedlmayr (1999) suggested that metallic iron particles may form as inclusions embedded in large silicate grains. Kemper et al. (2002) argued that nonspherical metallic particles can provide the 3-8 $\mu$m opacity needed to fit the spectral energy distribution of the OH/IR star OH 127.8+0.0, suggesting that iron particles may be produced in quiescent O-rich stellar outflows. Wickramasinghe & Wickramasinghe (1993) modeled the IR emission of Supernova 1987A and argued for the condensation of metallic needles in its ejecta with an amount of $\sim 8 \times 10^{-8} M_\odot$. As evolved stars and supernovae are the primary sources of the dust in the ISM (e.g., see Edmunds & Morgan 2005, Gomez et al. 2007, Dunne et al. 2009, Barlow et al. 2010, Matsuura et al. 2011), it is quite plausible that iron grains may be an appreciable dust constituent of the general ISM.

The growth of metallic whiskers under laboratory conditions has been extensively demonstrated for a large number of elements such as carbon, iron, aluminum, magnesium, potassium and mercury. Hoyle & Wickramasinghe (1988) postulated that the growth of metallic whiskers in supernova ejecta begins as more or less spherical clusters of atoms with a radius that increases to $\sim 0.01 \mu$m. Because of the appearance of a helical or screw-dislocation which becomes self-propagating along the direction of the whisker, the condensate grows linearly with great rapidity up to lengths of $\sim 1$ mm or more. They further attributed the origin of the screw dislocation to an occasional radioactive instability of cobalt atom that became incorporated in the initial more or less spherical growth of a condensate. According to Hoyle & Wickramasinghe (1988), the rate of whisker growth is exponential; for example, a needle of radius of 0.01 $\mu$m could grow to a length of $\sim 1$ mm in only $10^6$ yr in a typical protostellar environment. On the other hand, Piotrowski (1962) argued that elongated grains, if electrically charged, would grow longer through preferential capture of ions near the ends of the grain. In addition, there are also other processes that can produce chains of metallic (as well as insulating) particles in natural systems (e.g., the early solar nebula). Marshall et al. (2005) have experimentally shown that triboelectric charging of grains due to turbulent collisions followed by “head-to-tail” aggregation of the charged grains could lead to the formation of filamentary aggregates at enhanced aggregation rates. Nuth et al. (1994) and Nuth & Wilkinson (1995) have also both experimentally and theoretically shown that the formation of chains of very small ($\sim 20$ nm) iron grains in the solar nebula could be greatly enhanced due to magnetic dipole interactions. In both the electrostatic (Marshall et al. 2005) and magnetic (Nuth et al. 1994, Nuth & Wilkinson 1995) aggregated cases, there can be an almost infinite length to diameter ratio.

More recently, Nuth et al. (2010) have experimentally demonstrated the formation of abundant graphite whiskers on or from the surfaces of the graphite grains when they were repeatedly exposed to H$_2$, CO, and N$_2$ at 875 K, a condition mimicking that of protostellar nebulae. This naturally explains the discovery of graphite whiskers in carbonaceous chondrites (Fries & Steel 2008). Nuth et al. (2010) further argued that graphite whiskers could be expelled from protostellar systems either in polar jets or by radiation pressure and thus populate the interstellar space (also see Bland 2008). The protostellar-nebula origin of metallic whiskers may be advantageous over the circumstellar condensation scenario. While vapor-phase growth along the c-axis of a crystalline metal grain is possible, many freshly condensed grains in circumstellar environments would be frozen “liquid” drops and require annealing prior to crystallization since crystallization would be required to yield a c-axis to direct further growth. However, once the initial condensation growth phase ceases, there is generally no more condensable material left in the gas phase to add to the crystal along any axial direction. This restriction does not necessarily apply in a protostellar nebula where large scale mixing can occur (see Nuth et al. 2010).

In any case, to quantitatively evaluate the role of metallic needles in explaining the mid-IR interstellar extinction, the dimming of Type Ia supernovae, the thermalization of the cosmic microwave background, as well as the expulsion of metallic needles from stellar and protostellar systems, an accurate knowledge of the absorption cross sections of metallic needles over a wide wavelength range is required. We therefore call for rigorous calculations of the absorption cross sections of metallic needle-like particles of various aspect ratios, presumably with the discrete dipole approximation (DDA; Purcell & Pennypacker 1973, Draine 1988). However, we should also note that in the IR, the complex dielectric functions of metallic materials are very large and the DDA often does not give very accurate results. Also, cosmic needles could contain impurities, oxide coatings or other chemical heterogeneities. In addition, the needles found in astrophysical environments are not likely all single axis needles (because there is no significant axial stiffness as would be found in a crystalline needle), but might consist of elongated grain aggregates with significant numbers of kinks and bends along the primary axis. We therefore also call for systematic experimental explorations of the formation and growth mechanisms of metallic needle-like particles in conditions which may prevail in protostellar nebulae as well as experimental measurements of their absorption properties over a wide wavelength range from the UV to the far-IR, submillimeter and millimeter.
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ACKNOWLEDGEMENTS

We thank Drs. B.T. Draine, E. Dwek, F.Z. Liu, D. Pfenniger, and J.L. Puget for very helpful discussions. We are particularly indebted to Dr. J.A. Nuth whose stimulating comments and suggestions largely improved the presentation of this paper. CYX is supported in part by the Talents Recruiting Program of Beijing Normal University and the National Natural Science Foundation of China (NSFC) Grant No. U1731107. AL is supported in part by a NSF grant AST-1816411.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding authors.

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