Spinning Dust Emission from Circumstellar Disks and Its Role In Excess Microwave Emission

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Abstract

Electric dipole emission from rapidly spinning polycyclic aromatic hydrocarbons (PAHs) is widely believed to be an origin of anomalous microwave emission (AME), but recently it has encountered a setback owing to the noncorrelation of AME with PAH abundance seen in a full-sky analysis. Microwave observations for specific regions with well-constrained PAH features would be crucial to test the spinning dust hypothesis. In this paper, we present physical modeling of microwave emission from spinning PAHs from protoplanetary disks (PPDs) around Herbig Ae/Be stars and T Tauri stars where PAH features are well observed. Guided by the presence of 10 μm silicate features in some PPDs, we also model microwave emission from spinning nanosilicates. Thermal emission from big dust grains is computed using the Monte Carlo radiative transfer code (RADMC-3D). Our numerical results demonstrate that microwave emission from either spinning PAHs or spinning nanosilicates dominates over thermal dust at frequencies ν < 60 GHz, even in the presence of significant grain growth. Finally, we attempt to fit millimeter–centimeter observational data with both thermal dust and spinning dust for several disks around Herbig Ae/Be stars that exhibit PAH features and find that spinning dust can successfully reproduce the observed excess microwave emission (EME). Future radio observations with ngVLA, SKA, and ALMA Band 1 would be valuable for elucidating the origin of EME and potentially open a new window for probing nanoparticles in circumstellar disks.

Key words: circumstellar matter – dust, extinction – protoplanetary disks – radio continuum: planetary systems

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are an important dust component of the interstellar medium (ISM; see review by Tielens 2008). Following the absorption of ultraviolet (UV) photons, PAH molecules reemit radiation in mid-IR, producing prominent 3.3, 6.2, 7.7, 8.6, 11.3, and 17 μm features (Leger & Puget 1984; Allamandola et al. 1985; Draine & Li 2007; Smith et al. 2007). Rapidly spinning PAHs also emit electric dipole radiation in microwaves via a new mechanism, so-called spinning dust (Draine & Lazarian 1998; Hoang et al. 2010). The latter is the most likely origin of anomalous microwave emission (AME) that contaminates cosmic microwave background radiation (Kogut et al. 1996; Leitch et al. 1997; Planck Collaboration et al. 2011, 2016).

PAH molecules appear to be a natural carrier of the AME (Draine & Lazarian 1998; Planck Collaboration et al. 2011) because it is an established component of interstellar dust (Draine et al. 2007). Yet such an explanation has recently faced a setback owing to no correlation between the observed AME and PAH abundance based on a full-sky analysis by Hensley et al. (2016). Due to the spatial variation of PAH properties (e.g., geometry, size, and electric dipole moment), it is rather challenging to achieve a robust constraint for the carrier of AME by means of the full-sky analysis (see Dickinson et al. 2018, for a review). Therefore, observations of AME from specific regions with well-constrained PAH properties are critical to elucidate the exact carrier of AME.

PAH molecules are usually detected in circumstellar disks around Herbig Ae/Be stars and some T Tauri stars (Habart et al. 2004; Seok & Li 2017). Their presence in protoplanetary disks (PPDs) is puzzling because one expects that interstellar PAHs are already depleted in dense cores owing to coagulation. Thus, PAH molecules in PPDs may be newly formed particles as a result of dynamical processes, such as desorption of PAHs from the grain surface due to stellar radiation heating or replenishment due to collisions of planetesimals. PAHs can be formed in PPDs near the high-temperature and high-density regions (see Kamp 2011). Interestingly, if PAHs are produced by fragmentation of big carbonaceous grains, then we expect a population of silicate nanoparticles that can also be produced by fragmentation of big silicate grains. Note that the modeling of very small grains (VSGs) around Herbig Ae/Be stars is previously studied in Natta et al. (1993). Alternatively, nanoparticles (including PAHs and nanosilicates) may follow a different evolution from classical grains (size of 0.1 μm).

Thus, while classical dust grains are depleted in the disk owing to coagulation and settling, PAHs/VSGs that are well mixed to the gas can be exempt from grain settling and coagulation, and turbulence can be responsible for the mixing (see Dullemond et al. 2007).

The modern understanding of AME indicates that, in addition to spinning PAHs, rapidly spinning silicate nanoparticles can successfully reproduce the observed AME in the diffuse ISM (Hoang et al. 2016; Hensley & Draine 2017). Spinning iron nanoparticles cannot reproduce the entirety of the observed AME (Hoang et al. 2016). Although the presence of nanosilicates in the ISM remains a hypothesis, in contrast to PAHs, an analysis by Li & Draine (2001) shows that the
fraction of total Si abundance ($\text{Si}/\text{H} = 3.6 \times 10^{-5}$) contained in ultrasmall grains, denoted by $Y_{\text{Si}}$, can reach $Y_{\text{Si}} \sim 10\%$ without violating the observational constraints of the UV starlight extinction and mid-IR emission. Hoang et al. (2016) found that their emission and UV absorption do not violate the observational constraints for $Y_{\text{Si}} < 15\%$. As PAHs, we expect that nanosilicates are present in PPDs as a component of the dust evolution model (see Natta et al. 2007). Indeed, Seok & Li (2017) found strong 9.7 $\mu$m emission Si-O features by nanosilicates in 40 out of 61 circumstellar disks (see Keller et al. 2008).

Rafikov (2006) carried out a simple modeling of microwave emission by spinning PAHs for the fiducial disks around T Tauri ($M_{\star} < 2M_{\odot}$) and Herbig A/Be stars ($2M_{\odot} \leq M_{\star} < 10M_{\odot}$). Assuming a 1D disk structure, the author found that spinning dust emission dominates over thermal dust emission for $\nu < 60\,\text{GHz}$.

Radio observations of circumstellar disks often show excess emission at microwave frequencies, i.e., $\nu < 100\,\text{GHz}$, above what is extrapolated from thermal dust emission at sub (millimeter) wavelengths, which we term excess microwave emission (EME). For instance, Very Large Array (VLA) observations by Calvet et al. (2002) and Natta et al. (2004) reveal EME at 7 mm ($\nu \sim 43\,\text{GHz}$) from the disk around T Tauri star TW Hya, whereas Wilner et al. (2005) found excess emission at 3.5 cm ($\nu = 9\,\text{GHz}$). The authors explained EME by thermal emission from very big grains (i.e., centimeter-sized grains). EME is also detected in circumstellar disks around Herbig Ae/Be stars (Skinner et al. 1993; Dent et al. 2006; Sandell et al. 2011). Although thermal dust from very big grains and free–free emission from winds are believed to be responsible for such excess emission, the exact mechanism is still unclear. Very recently, Ubach et al. (2017) found EME in 11 disks around T Tauri stars and suggested that multiple mechanisms different from thermal dust may be responsible for EME. To better understand the origin of EME, we will explore whether spinning dust could reproduce the observed EME.

With high resolution and low frequencies, next-generation VLA (ngVLA), ALMA Band 1, and SKA would be useful for observing spinning dust emission from circumstellar disks around T Tauri and Herbig A/Be stars (Di Francesco et al. 2013; Scaife 2013). Radio observations by SKA and ALMA Band 1 would be crucial to study grain growth from millimeter- to centimeter-sized pebbles as a first step of planet formation (Testi et al. 2015).

To provide more realistic predictions for future observations, in this paper we will improve modeling of microwave emission from Rafikov (2006) by (1) treating the realistic geometry (i.e., 2D), (2) finding the dust grain temperature using the publicly available 3D Monte Carlo radiative transfer code (RADMC-3D; Dullemond et al. 2012), (3) considering emission from both the disk interior and surface layers, and (4) accounting for microwave emission from spinning nanosilicates. We also perform modeling of thermal dust emission with grain growth to 10 cm, in order to quantify the simultaneous effect of grain growth and spinning dust on the spectral energy distribution (SED).

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7 EME is different from AME in the sense that the latter is the excess emission left after removing all three known galactic emission components, including thermal emission, free emission, and synchrotron.

8 The code and user guide are available at http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/.
where $H_0$ is the aspect ratio at the reference radius $R_0$. For $R_0 = 100$ au, $H_0/R_0$ is taken to be 0.1 as a fiducial model, which corresponds to $H_0/R = 0.1 \times 3^{1/7}$ at $R_{\text{out}} = 300$ au. Although the chosen aspect ratio is much lower than predicted by Chiang & Goldreich (1997), it is comparable to observations (Avenhaus et al. 2018).

The typical value $\alpha = 1$ is adopted. Other physical parameters, including $R_{\text{in}}$ and $R_{\text{out}}$, are listed in Table 1.

### 2.2. Gas and Dust Temperatures

Following the popular model of protoplanetary disks (Chiang & Goldreich 1997), the surface layer is defined by a path of optical depth $\tau_T = 1$. At distance $r$ from the star, the surface layer is heated to a high temperature $T_s$ by stellar radiation. Subsequent collisions with gas atoms result in gas heating. Dust grains in these superheated layers reemit radiation in IR that in turn heats gas and dust in the disk interior to a temperature $T_P$. For an isothermal disk, gas and dust are in thermal equilibrium, so that $T_P = T_{\text{gas}}$.

In our paper, instead of using the simplified temperature profile as in Rafikov (2006), we directly compute the dust temperature for the realistic disk model using RADMC-3D. The dust opacity is calculated assuming a power grain size, with different values of $a_{\text{max}}$ for silicate grains.

Figure 2 shows the gas density and temperature for a fiducial disk around Herbig Ae/Be stars. The obtained dust temperature depends on $a_{\text{max}}$ because of the opacity $\kappa$.

### 2.3. Gas Ionization and Charge of PAHs/VSGs

Gas in PPDs can be ionized by X-rays, far-UV photons, and cosmic rays (see Perez-Becker & Chiang 2011, and references therein). Theoretical estimates provide the hydrogen ionization fraction $X_H \sim 10^{-6}$--$10^{-7}$ for the surface layer and $X_H \sim 10^{-10}$ for the disk interior (Perez-Becker & Chiang 2011).

The ionization of PAHs/VSGs can be approximately described by a three-layer vertical structure model (Visser et al. 2007). In the surface layers, PAHs/VSGs are positively charged owing to photoelectric emission induced by stellar UV photons. In the intermediate region, PAHs/VSGs are mostly neutral, reflecting the balance of photoelectric emission and electron captures, and PAHs/VSGs are negatively charged in the disk plane owing to electron collisions and the lack of UV photons (see Kamp 2011; also Maaskant et al. 2014). Nevertheless, as shown in the next section, the effect of PAH and nanoparticle charge states is not important for grain rotation in very dense environments such as PPDs.

### 3. Spinning Dust Model

#### 3.1. Electric Dipole Moment and Emission Power

The rotational emission mechanism is built on the assumption that nanoparticles own nonzero electric dipole moments. PAH molecules can acquire intrinsic dipole moments owing to polar bonds (see Draine & Lazarian 1998). The attachment of SiO and SiC molecules to the grain surface gives rise to the electric dipole moment for nanosilicates (Hoang et al. 2016).

Let $N$ be the total number of atoms in a nanoparticle of effective size $a$ that is defined as the radius of an equivalent sphere of the same volume. Assuming PAHs with a typical structure C:H = 3:1 having mean mass per atom $m = 9.25$ au, one obtains $N = 545a^{3/7}$ with $a = \alpha/10^{-7}$ cm, for the mass density $\rho = 2$ g cm$^{-3}$ (Draine & Lazarian 1998). Assuming nanosilicates with a structure SiO$_{3}$Mg$_{1}$Fe$_{0.5}$, having $m = 24.15$ au, one has $N = 418a^{3/7}$ in $\rho = 4$ g cm$^{-3}$ (Hoang et al. 2016).

Let $\beta$ be the dipole moment per atom in the grain. Assuming that dipoles have a random orientation distribution, the intrinsic dipole moment of the grain can be estimated using the random walk formula:

$$\mu^2 = N\beta^2 \approx 86.5(\beta/0.4D)^2a^{3/7}D^2$$  

for PAHs, and $\mu^2 \approx 66.8(\beta/0.4D)^2a^{3/7}D^2$ for nanosilicates (Hoang et al. 2016).

The power emitted by a rotating dipole moment $\mu$ at angular velocity $\omega$ is given by the Larmor formula:

$$P(\omega, \mu) = \frac{2}{3} \omega^4 \mu^2 \sin^2 \theta c^3,$$

where $\theta$ is the angle between $\omega$ and $\mu$. Assuming a uniform distribution of the dipole orientation, $\theta$, $\sin^2 \theta$ is replaced by $\langle \sin^2 \theta \rangle = 2/3$.

#### 3.2. Rotational Damping and Excitation Coefficients

Rotational damping and excitation for nanoparticles, in general, arise from collisions between the grain and gaseous atoms (neutrals and ions) followed by the evaporation of atoms/molecules from the grain surface, absorption of starlight, and IR emission (Draine & Lazarian 1998; Hoang et al. 2010). Moreover, the distant interaction between the grain electric dipole and electric field induced by passing ions results in an additional effect, namely, plasma drag. The rotational damping and excitation for these processes are respectively described by the dimensionless damping coefficients $F_j$ and $G_j$, where $j = n, i, p, \rho$, IR denotes the neutral–grain collision, ion–grain collision, plasma drag, and IR emission, respectively (see Hoang et al. 2010).

We consider the major neutral components in the PPDs, including H, H$_2$, He, and ions H$^+$ and C$^+$. The typical values are $x_H = 10^{-8}$, $n(\text{He}) \sim 0.1n_H$, $y = 2n(\text{H}_2)/n_H \sim 2$, and $x_M = n(\text{C}^+)/n_H \approx 10^{-8}$.

Let $T_{\text{rot}}$ be the rotational temperature of spinning nanoparticles, so that $3kT_{\text{rot}} = \hbar \langle \omega^2 \rangle$. Thus, using the rms angular velocity from Draine & Lazarian (1998), we obtain

$$\frac{T_{\text{rot}}}{T_{\text{gas}}} = \frac{G}{F} \left[ 1 + \left(\frac{G}{F}\right)(20\tau_H/3\tau_{\text{ed}})^2 \right]^{1/2},$$

where $\tau_H$ and $\tau_{\text{ed}}$ are the characteristic damping times due to gas collisions and electric dipole emission, respectively (see Draine & Lazarian 1998). From Figure 1 we see that the majority of the disk has $\tau_H > 10^5$ cm$^{-3}$, which results in $\tau_{\text{ed}}/\tau_H \sim (a/3.5$ Å$)^2(n_H/10^4$ cm$^{-3}) > 1$ (see Hoang et al. 2010). Thus, $T_{\text{rot}}/T_{\text{gas}} \sim G/F$, i.e., the rotational temperature is only determined by $F$ and $G$ coefficients.
Figure 3 shows the $F$ and $G$ coefficients for neutral PAHs at three locations in the disk plane at 50, 100, and 200 au. The corresponding gas density is $n_H = 10^8$, $10^9$, and $10^{10}$ cm$^{-3}$ (see Equation (2)). The radiation intensity factor is $U = 4 \times 10^3$, $2 \times 10^4$, and $10^3$ (see Equation (17)). A typical ionization fraction $x_{\text{H}} = 10^{-8}$ is chosen. In all three locations, collisional interactions with neutral dominate the damping and excitation. In Figure 4, we show the results for negatively charged PAHs. Collisions still dominate the interaction, such that the evaporation is $T_{\text{ev}} = T_{\text{gas}}$, leading to the detailed balance with $F_u = G_u$.

In the disk interior with anion PAHs, the ionization fraction is too low, i.e., $x_{\text{H}} < 10^{-8}$, and ion excitation and plasma drag are not important, as shown in Figure 3. In the surface layer with higher ionization fraction ($x_{\text{H}} \sim 10^{-5}$), rotational excitation by neutral-positively charged PAH can be efficient. Nevertheless, the mass of the surface layer is very low compared to the total disk mass, such that the ionization effect has little impact on the net spinning dust emission. As a result, in the following we can adequately assume $T_{\text{rot}} = T_{\text{gas}}$ for modeling spinning dust throughout the disk.
3.3. Angular Momentum Distribution Function

In high-density conditions where collisional excitations dominate rotation of nanoparticles (e.g., in PPDs), the grain angular momentum can be appropriately described by the Maxwellian distribution:

\[
f(T, I) = \frac{I^{3/2}}{(2\pi)^{3/2}} \frac{\omega^2}{(kT_{\text{rot}})^{3/2}} \exp \left( -\frac{I \omega^2}{2kT_{\text{rot}}} \right),
\]

where \( I = \frac{8\pi p a^5}{15} \) is the moment of inertia of the spherical nanoparticle of mass density \( p \).

3.4. Size Distribution: PAHs and Nanosilicates

Following Li & Draine (2001), nanoparticles are assumed to follow a lognormal size distribution:

\[
f_n(a) = B_j a^\sigma_j \exp \left( -\frac{\log(a/a_0,j)}{\sigma_j} \right)^2,
\]

where \( j = \text{PAH, sil} \) corresponds to PAHs and nanosilicate composition, respectively, \( a_0,j \) and \( \sigma_j \) are the model parameters, and \( B_j \) is a constant determined by

\[
B_j = \frac{3}{(2\pi)^{3/2}} \frac{\exp(-4.5\sigma_j^2)}{\rho \sigma_0^3 a_{0,j}^2} \times \left( \frac{m_X}{1 + \text{erf}[3\sigma/a_0]/\sigma] \right),
\]

where \( b_X = X H \rho_X \) with \( Y_X \) being the fraction of \( X \) abundance contained in very small sizes and \( X_H \) being the solar abundance of element \( X \), \( m_X \) is the grain mass per atom \( X \). In our studies, \( X = C \) for PAHs and \( X = \text{Si} \) for nanosilicates.

The peak of the mass distribution \( a \partial n / \partial \ln a \) occurs at \( a_p = a_0,j e^{\ln(3) \sigma_j} \). Three parameters determine the size distribution of nanoparticles: \( a_0,j, \sigma_j, \) and \( Y_X \).

In realistic environments, \( b_X \) should depend on the local conditions and is a function of the radial distance \( R \). However, due to poorly known nanoparticles in the disk, \( b_X \) is kept constant in this paper.

3.5. Spinning Dust Emissivity and Emission Spectrum

Let \( j_{\nu}(\mu, T_{\text{rot}}) \) be the emissivity from a spinning nanoparticle of size \( a \) at location \((r, \theta, \phi)\) in the disk, where \( T_{\text{rot}} \) in general is a function of the local conditions. Thus,

\[
j_{\nu}(\mu, T_{\text{rot}}) = f_{\omega}(\omega, \mu) \frac{4\pi}{2\pi} \frac{\omega}{2kT_{\text{rot}}},
\]

where \( f_{\omega} \) is given by Equation (7).

The rotational emissivity per H nucleon is obtained by integrating over the grain size distribution (see Hoang et al. 2011):

\[
j_{\nu}(\mu, T_{\text{rot}}) = \int_{a_{\text{min}}}^{a_{\text{max}}} f_{\nu}(\mu, \omega, T_{\text{rot}}) \frac{1}{n_H} \frac{dn}{da},
\]

where \( d\nu/da = d\nu_{PAH,sil}/da \) for spinning PAHs and nanosilicates, respectively.

Thus, the total emission luminosity from the disk is given by

\[
L_{\nu,\text{sd}} = \int_{R_{\text{in}}}^{R_{\text{out}}} r^2 \sin \theta d\theta \int_0^{2\pi} d\phi \int_{\Delta n_H(R, z)} d\nu \left( \frac{4\pi j_{\nu}(\mu, T_{\text{rot}})}{n_H} \right),
\]

where

\[
\begin{align*}
L_{\nu,\text{sd}} &= \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi R \, dR \int d\nu \int_{\Delta n_H(R, z)} d\nu \left( \frac{4\pi j_{\nu}(\mu, T_{\text{rot}})}{n_H} \right), \\
&= \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi R \, dR \int d\nu \int_{\Delta n_H(R, z)} d\nu \left( \frac{4\pi j_{\nu}(\mu, T_{\text{rot}})}{n_H} \right). 
\end{align*}
\]
The slope is shallower for larger grains, but it does not follow the power law.

where \( n_d(R, z) \) is given by Equation (2). For a disk at distance \( D \) from the observer, the spectral flux density of spinning dust \( F_d = L_{\nu, sd}/4\pi D^2 \).

4. Thermal Dust Emission

4.1. Dust Opacity

Let \( Q_{abs}(a, \nu) \) be the absorption efficiency for a grain of radius \( a \) at frequency \( \nu \). The density of dust grains is given by the grain size distribution \( dn_g/da \). The dust opacity, defined as the total absorption cross section per unit of dust mass, is given by

\[
\kappa_{abs}(\nu) = \frac{\int_{a_{min}}^{a_{max}} \pi a^2 Q_{abs}(a, \nu)(dn_g/da)da}{\int_{a_{min}}^{a_{max}} (4\pi a^3/3)(dn_g/da)da},
\]

where \( a_{min, max} \) are the lower and upper cutoffs of the size distribution of big grains. Here \( a_{min} = 0.01 \ \mu m \) is chosen, and \( a_{max} \) is varied to account for grain growth.

We compute the absorption cross section for spherical grains using the Mie theory coded from Bohren & Huffman (1983), assuming the optical constant of amorphous silicate \((\text{Mg}_0.7\text{Fe}_{0.3}\text{SiO}_3)\).\(^9\) The opacity is then calculated by Equation (13), assuming the power law of the grain size distribution \( dn_g/da \propto a^{-q} \).

Figure 5 shows the dust opacity for the different values of \( a_{max} \), assuming the typical value \( q = -3.5 \) and a shallower distribution of \( q = -2.5 \). The grain growth from 1 to 10 cm can increase the opacity at \( \nu < 30 \ \text{GHz} \) by a factor of 2. The distribution of \( q = -2.5 \) results in an increase of the opacity at \( \nu \sim 10-100 \ \text{GHz} \). Note that the opacity at \( \nu = 30 \ \text{GHz} \) does not increase monotonically with \( a_{max} \).

4.2. Thermal Dust Emission

In the case of an isothermal disk along the vertical direction, the spectral flux density of thermal emission from the disk in the optically thin regime can be calculated by

\[
F_{th} = \frac{1}{4\pi D^2} \int_{R_{in}}^{R_{out}} \pi B_\nu(T_d) (1 - e^{-\kappa_{abs}(\nu)S(\nu)\tau(R)}) 2\pi R dR,
\]

where \( \kappa_{abs}(\nu) \) is given by Equation (13).

In the present paper, we directly compute \( F_{th} \) using RADMC-3D for the different grain size distributions and \( a_{max} \). This allows us to relate the SED of thermal dust to the effect of grain growth.

5. Spinning Dust Emission Spectrum from Circumstellar Disks

5.1. Numerical Method and Model Setup

Our modeling strategy is depicted in Figure 6. We adopt the fiducial model of a circumstellar disk around a Herbig Ae/Be star and T Tauri star, with physical parameters listed in Table 1. For a set of the disk parameters, \( T_d, R_d, \alpha \), we create a disk physical model as described in Section 2 to generate the gas density profile \( n_g(R, \theta, \phi) \). We then use RADMC-3D to calculate \( T_d(r, \theta, \phi) \) for the constructed disk. We consider the different grain size distributions, which have opacity given by Figure 5. Viscous heating and internal heating are not considered. For MC simulations, we use the default value of \( N_{phot} \sim 10^5 \) photon packages. The grid resolutions are \( N_r = 128, N_\theta = 32, N_\phi = 128 \), in which \( R \) spans from \( R_{min} \) to \( R_{out} \), \( \theta \) from \( \pi/3 \) to \( 2\pi/3 \), and \( \phi \) from 0 to \( 2\pi \).

At each location \( (r, \theta, \phi) \) with given local physical parameters \( (n_{g}, T_{gas}) \), we can calculate the damping and excitation coefficients \( F \) and \( G \) to obtain \( T_{rot} \) using Equation (6). This process can be simplified by the fact that, in the dense conditions, \( T_{rot} \sim T_{gas} \). The spinning dust emissivity \( j_d(r, \theta, \phi)\) is then calculated using Equation (11). Finally, the energy flux density of spinning dust is calculated by integrating over the symmetric disk as given by Equation (12).

5.2. Microwave Emission from Spinning PAHs

We first consider the emission from spinning PAHs. The PAH size distribution is varied from \( (a_{min}, \sigma) = (0.2 \ \text{Å}, 0.2) \) to \( (0.5 \ \text{Å}, 0.5) \). Here we fix the C abundance contained in PAHs, \( f_C \), to be similar to that of the diffuse ISM, \( f_C \sim 0.05 \) (see Draine & Li 2007).\(^{10}\) The lower and upper cutoffs of the PAH size distribution are \( a_{min} = 3.5 \ \text{Å} \) and \( a_{max} = 100 \ \text{Å} \).

\(^9\) http://www.astro.uni-jena.de/Laboratory/OCDB/data/silicate/amorph/pymg70.html

\(^{10}\) The effect of varying \( f_C \) is analogous to spinning nanosilicates, which will be quantified in the next section.
Figure 7 shows the spectral flux density of spinning PAH emission from both the disk interior and surface layer for a Herbig Ae/Be (left panel) and T Tauri (right panel) disks. Models with smaller PAHs tend to have stronger emission and higher peak frequency.

Figure 8 shows the ratio of spectral flux density from spinning PAHs to thermal dust. Emission from spinning PAHs dominates the thermal dust for frequency \( \nu \) < 100 GHz for Herbig Ae/Be disks and \( \nu \) < 40 GHz for T Tauri disks.

5.3. Microwave Emission from Spinning Nanosilicates

Nanosilicates are expected to have a larger lower cutoff owing to more efficient sublimation, as in Hensley & Draine (2017); thus, we adopt \( a_{\text{min}} = 4.5 \) Å. We now vary the Si abundance contained in nanoparticles from \( Y_{\text{Si}} = 0.01 \) to 0.2, while the size distribution parameters are fixed with \( a_0 = 3 \) Å and \( \sigma = 0.3 \). Indeed, the variation of \( (a_0, \sigma) \) should produce a similar behavior to that in spinning PAH emission because the physics is the same.

In Figure 9, we plot five spectra of the spinning dust from the disk for the different values of \( Y_{\text{Si}} \). Emission from spinning nanosilicates is as strong as spinning PAHs for \( Y_{\text{Si}} = 0.05 \), as expected, although the maximum emissivity occurs at a lower frequency because of smaller \( a_{\text{min}} \). Spinning dust flux is increased with increasing \( Y_{\text{Si}} \). The total emission from spinning PAHs and nanosilicates is much greater than the thermal dust emission at \( \nu < 100 \) GHz.

Figure 10 shows the ratio of spinning dust to thermal dust flux densities. The spinning dust dominates over the thermal dust for \( \nu < 60 \) GHz, even with only 1% of Si abundance contained in nanoparticles.

5.4. Effect of Grain Growth on Millimeter–Centimeter Thermal Emission

To quantify the effect of grain growth on millimeter–centimeter thermal emission, in Figure 11 we show the thermal emission for the different \( a_{\text{max}} \) spanning from 0.1 mm to 10 cm. The variation of thermal emission is noticeable for \( \nu \sim 30–100 \) GHz, but the increase in thermal...
emission from $a_{\text{max}} = 5 \text{ mm}$ to $a_{\text{max}} = 5 \text{ cm}$ is negligible at $\nu \sim 30$–$100 \text{ GHz}$.

Figure 12 shows the ratio $F_{\text{sd}}/F_{\text{th}}$ for the different values of $a_{\text{max}}$. The increase from $a_{\text{max}} = 1 \text{ mm}$ to $1 \text{ cm}$ increases the thermal dust emission significantly, resulting in the reduction of $F_{\text{sd}}/F_{\text{th}}$ by an order of magnitude. The shallower size distribution helps to enhance thermal dust emission. However, spinning dust is still dominant at frequencies below $60 \text{ GHz}$. The dashed lines show that even only 1% of Si contained in nanosilicates can still produce substantial microwave emission compared to thermal dust with grain growth at $\nu < 30 \text{ GHz}$.

6. Discussion

6.1. PAHs/Nanoparticles Traced by Mid-IR Emission and Implication for Spinning Dust

PAH molecules are widely detected in circumstellar disks around Herbig Ae/Be stars and some T Tauri stars (Habart et al. 2004; Seok & Li 2017). The presence of nanosilicates is also demonstrated by 9.7 $\mu$m emission features present in many PPDs (Seok & Li 2017).

Recently, modeling works have been done to constrain the physical properties of PAHs. Li & Lunine (2003) inferred the PAH size distribution $(a_0, \sigma)$ by fitting the mid-IR spectrum for the disk around HD 141569A. Seok & Li (2017) derived the PAH size distribution and the total mass of PAHs in about 60 disks around Herbig Ae/Be and T Tauri stars. The authors found that small PAHs, characterized by $(a_0, \sigma) \sim (2 \text{ Å}, 0.2)$, are ubiquitous in PPDs.

If the size distribution of nanoparticles from the shielded region is not different from the surface layer,11 as constrained by mid-IR features, then many disks that have small PAHs inferred in Seok & Li (2017) would provide strong spinning dust emission, provided that C abundance in PAHs $b_C > 0.01$ (see Figure 8). These disks appear to be the most favorable targets for future observations of spinning dust.

11 Apparently, the PAH parameters describe PAH molecules from the surface layer directly illuminated by UV radiation. Nevertheless, the vertical mixing is efficient owing to turbulence (Siebenmorgen & Krügel 2010; Siebenmorgen & Heymann 2012), leading to the frequent circulation of PAHs and nanoparticles between the surface layer and disk interior.

6.2. Comparison to Previous Works

Rafikov (2006) carried out a 1D modeling of microwave emission from spinning PAHs for the disk interior for fiducial disks around Herbig Ae/Be, T Tauri, and brown dwarf stars. Rafikov (2006) assumed the thermal rotation (i.e., $T_{\text{rot}} = T_{\text{gas}}$) and adopted the standard size distribution of PAHs from the diffuse ISM, with $b_C = 0.05$. The gas and dust temperature is assumed to follow an analytical formula as a function of the radial distance. Thermal dust is modeled by a power law with a constant spectral slope $\beta$, although the slope $\beta$ at $\nu < 100 \text{ GHz}$ is not a simple function of the maximum grain size $a_{\text{max}}$ (see Figure 5).

In this paper, we have performed self-consistent, 2D modeling of spinning dust emission (including radial and vertical structures), which is combined with Monte Carlo radiative transfer modeling of thermal dust emission using RADMC-3D. In this way, we naturally account for spinning dust emission from both the surface layer and disk interior. We considered a variety of PAH size distributions $(a_0, \sigma)$ that capture the inferred distribution from mid-IR emission (see the preceding section). Moreover, we took into account the emission from rapidly spinning silicate nanoparticles (Hoang et al. 2016; Hensley & Draine 2017). We found that microwave emission from nanosilicates could significantly increase the SED at $\nu < 60 \text{ GHz}$, making the detection easier than spinning PAHs alone. Previous studies by Hoang et al. (2016) show that Si abundance $Y_{\text{Si}}$ can reach 10% without violating observational constraints in UV extinction, AME polarization, and IR emission. We find that even $Y_{\text{Si}} = 0.01$ can produce the AME by a factor of 10 larger than the thermal dust for $\nu \sim 30 \text{ GHz}$.

In particular, the flux density of thermal dust emission from a circumstellar disk is calculated by RADMC-3D for the different dust size distributions in the presence of grain growth with $a_{\text{max}}$ spanning from 0.1 mm to 10 cm. The simultaneous modeling of spinning dust and thermal dust with grain growth allows us to quantify the respective contribution to microwave emission by these two mechanisms as a function of the nanoparticle size distribution and maximum values $a_{\text{max}}$. 

Figure 9. Spectral flux density from spinning nanosilicates (dotted lines), thermal dust (dashed line), and the total emission (solid lines). The Si abundance in nanoparticle particles is varied between $Y_S = 0.01$ and 0.2. Left and right panels show the results for Herbig Ae/Be disks and T Tauri disks, respectively.
6.3. Can Spinning Dust Explain EME from Circumstellar Disks?

6.3.1. EME from Disks

EME is often found in radio observations from circumstellar disks around Herbig Ae/Be stars (Skinner et al. 1993; Meeus et al. 2001; Dent et al. 2006; Sandell et al. 2011; van der Plas et al. 2016), as well as T Tauri stars (Kalvèt et al. 2002; Natta et al. 2004; Wilner et al. 2005; Ubach et al. 2012). The popular explanations for such EME include thermal dust emission from centimeter-sized grains and free-free emission from winds/jets (see, e.g., Ubach et al. 2012). Recently, Ubach et al. (2017) observed the emission excess from 11 disks around T Tauri stars and suggested that multiple mechanisms should be responsible for EME.

6.3.2. Spinning Dust as an Origin of EME

Investigating observational data collected from the literature presented in Sandell et al. (2011), one can see that the Herbig Ae/Be disks with prominent EME include R Mon, HD 35187, HD 163296, and HD 169142. Interestingly, the last three disks also exhibit prominent PAH emission (see Seok & Li 2017), while weak PAH emission is observed in the R Mon disk (Verhoef et al. 2012). The HD 35187 and HD 163296 disks also exhibit strong 9.7 μm silicate emission. Thus, we expect some contribution of spinning dust to the observed EME.

To explore whether spinning dust can explain EME from circumstellar disks, we first fit the observational data with a two-component model, including thermal dust and spinning dust. The total flux density is described by

\[ F_{\text{mod}}(\nu) = F_{\text{sd},100} \left( \frac{\nu}{100 \, \text{GHz}} \right)^{\alpha_{\text{sd}}} + F_{\text{sd},0} \left( \frac{\nu}{\nu_{\text{pk}}} \right)^2 \exp \left[ 1 - \left( \frac{\nu}{\nu_{\text{pk}}} \right)^2 \right], \]

where \( \nu_{\text{pk}} \) and \( F_{\text{sd},0} \) are the frequency and the flux density at the peak of the spinning dust spectrum, respectively (see Draine & Hensley 2012). \( F_{\text{sd},100} \) is the thermal emission flux density measured at 100 GHz, and \( \alpha_{\text{sd}} = \beta + 2 \), with \( \beta \) the spectral slope of the dust opacity. The model parameters include \( F_{\text{sd},100}, \beta, F_{\text{sd},0}, \) and \( \nu_{\text{pk}} \),

The goodness of fit to the observed flux, \( F_{\text{obs}}(\nu) \), is measured by \( \chi^2 \), as defined by

\[ \chi^2 = \sum_j \left( \frac{F_{\text{mod}}(\nu_j) - F_{\text{obs}}(\nu_j)}{\sigma_j} \right)^2, \]

where \( \sigma_j \) is the data uncertainty at the data point \( \nu_j \) which is fixed to be 20% of \( F_{\text{obs}}(\nu_j) \). We infer the best-fit model parameters by minimizing \( \chi^2 \) using the Levenberg–Marquardt method from the publicly available package LMFIT (Newville et al. 2014). We fit to the millimeter–centimeter (i.e., \( \nu < 1000 \, \text{GHz} \)) data obtained from Sandell et al. (2011) and Meeus et al. (2001). In Figure 13, we show our two-component fits to the observational data for four disks around Herbig Ae/Be stars. For R Mon and HD 163296 disks, the required spinning dust flux is \( F_{\text{sd},0} \sim 0.5–1 \, \text{mJy} \), which can easily be reproduced with the low PAH/Si abundance of \( Y = 0.01 \) (see Figure 9). To reproduce the data for HD 163296, it requires spinning dust to peak at \( \nu_{\text{pk}} \sim 8.5 \, \text{GHz} \), while HD 169142 requires \( \nu_{\text{pk}} \sim 60 \, \text{GHz} \). Incidentally, mid-IR modeling by Seok & Li (2017) finds that the HD 169142 disk contains small PAHs (i.e., \( a_0, \sigma = (2.5 \, \text{Å}, 0.2) \)), while the HD 163296 disk contains larger PAHs (i.e., \( a_0, \sigma = (4.0 \, \text{Å}, 0.2) \)). Such small/large PAHs are predicted to strongly emit microwave emission with a high/low peak frequency (see Figure 7), consistent with the peak frequencies inferred from the model fitting.

Our best-fit thermal dust yields \( \beta \sim 0.5–1.2 \), implying the presence of centimeter-sized grains in these disks (see Draine 2006). The study of pebbles and planetesimals in PPDs using ALMA Band 1–3 and SKA (see, e.g., Testi et al. 2015) would suffer contamination from spinning dust at \( \nu < 100 \, \text{GHz} \). Therefore, to achieve a realistic measurement of the thermal dust spectral slope \( \beta \) and realistic understanding

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\( ^{12} \)Due to the limited observational data at \( \nu < 100 \, \text{GHz} \), we fit with a parametric model instead of performing physical modeling of spinning dust because the physical model depends on ~10 parameters (e.g., dipole moment, size distribution, and gas density and temperature). A three-component fitting, including thermal dust, spinning dust, and free-free emission, is also not feasible owing to the same reason.
of planet formation, spinning dust needs to be carefully modeled and separated from the observational data.

6.3.3. On the Importance of Free–Free Emission

At microwave frequencies, free–free emission from stellar winds or ionized jets is expected to be important in circumstellar disks. Its emission flux can be described by a power law, \( F_{\nu} \propto \nu^{-\alpha_{ff}} \), where \( \alpha_{ff} \) is the spectral slope. For optically thin regions, \( \alpha_{ff} = -0.1 \), but \( \alpha_{ff} \) becomes positive and can reach \( \alpha_{ff} \approx 2 \) for optically thick regions (Reynolds 1986). With this wide range of values, free–free emission is a leading mechanism to explain the EME (see Ubach et al. 2017). Here, we have also attempted to fit the EME with a model consisting of free–free emission and thermal dust emission. As expected, free–free emission can provide an equally good fit to the observational data as spinning dust. Specifically, the best-fit spectral index is \( \alpha_{ff} \approx 0.7 \) for R Mon, \( \sim 1 \) for HD 164192, \( -0.02 \) for HD 163296, and \( -0.1 \) for HD 35187.

Finally, we should stress that, except R Mon and HD 163296, two other disks (HD 35187 and HD 169142) have insufficient data points below 100 GHz to allow a robust constraint on the actual role of spinning dust for EME. Future multifrequency observations between 1 and 60 GHz by SKA, ngVLA, and ALMA Band 1 and 2 (Fuller et al. 2016) would be valuable to differentiate spinning dust and free–free emission as an origin of EME in circumstellar disks. Moreover, polarization observations would be particularly useful because free–free emission is unpolarized. It also can constrain the carriers of AME because the polarization of spinning nanosilicate emission is expected to be higher than that of spinning PAHs (Hoang & Lazarian 2016).

6.4. Toward Probing Nanoparticles in Circumstellar Disks via Spinning Dust

PAHs and nanoparticles are expected to play an important role in gas heating, chemistry, and dynamics of disks because they contribute the largest surface area for charge carrier and
Astrochemical activities (see Akimkin et al. 2013). Indeed, nanoparticles characterize the ionization level of the disk interior, which affects the magnetohydrodynamic instability activity and the dead zones (Fleming & Stone 2003). The probe of PAHs through mid-IR emission is limited mostly to the surface region, where PAHs are directly exposed to the stellar UV radiation. Therefore, the detection of spinning dust emission in PPDs not only is a smoking gun for the PAHs as a carrier of AME but also provides a new diagnostic for nanoparticles in the entire volume of PPDs.

The nondetection of AME from the disk with prominent PAH features but no silicate emission features would provide a convincing test for spinning PAHs as a carrier of the AME. Similarly, the detection/nondetection of AME from the disks with silicate features would provide a valuable test for the spinning nanosilicates as a carrier of AME.

It is worth mentioning that (sub)millimeter-wavelength observations usually reveal central cavities and gaps in transitional disks (e.g., HD 169142; Fedele et al. 2017). This indicates that significant grain growth has occurred, and its thermal emission is substantially reduced in (sub)millimeter wavelengths. If the assumption of PAHs/VSGs mixed to the gas is valid, then we expect to detect spinning dust emission by these nanoparticles from cavities and gaps. Therefore, transitional disks appear to be excellent targets to study spinning dust with future high-resolution experiments like ALMA Band 1, ngVLA, and SKA. Interestingly, a marginal detection of 33 GHz signal from the intracavity in MWC 758 has recently been reported by Casassus et al. (2018), which is suggested to be spinning dust emission.

**7. Summary**

We studied microwave emission from rapidly spinning nanoparticles from circumstellar disks around Herbig Ae/Be stars and applied it to explain the observed EME. The principal results are summarized as follows:

1. We performed a physical, 2D modeling of microwave emission from both rapidly spinning PAHs and spinning nanosilicates in circumstellar disks that include both the disk interior and surface layers. The dust temperature is numerically computed using the Monte Carlo radiative transfer code (RADMC-3D).

2. We found that microwave emission from either spinning PAHs or spinning nanosilicates can dominate over thermal dust at frequencies $\nu < 60$ GHz in circumstellar disks. The presence of both spinning nanosilicates and
PAHs can significantly increase the spectral flux density at $\nu < 100$ GHz. Our obtained results imply that the possibility of detecting spinning dust emission in PPDs is much higher than previously thought.

3. By simultaneous modeling of spinning dust and thermal dust emission for a physical disk model, we showed that the thermal dust is still much lower than spinning dust at $\nu < 60$ GHz; even the maximum grain size is increased by 10 cm. The presence of spinning dust emission would complicate the probe of grain growth and formation of planetesimals using radio observations.

4. Our two-component (thermal dust and spinning dust) model fitting to the millimeter-centimeter observational data of several Herbig Ae/Be disks (R Mon, HD 163296, HD 35187, and HD 169142) reveals that spinning dust can reproduce EME from the disks. Future multi-frequency observations by ALMA, ngVLA, and SKA would be valuable for elucidating the origin of EME as well as AME. Polarization observations would help to distinguish the carriers (PAHs or nanosilicates) of AME. Detection of spinning dust emission in circumstellar disks would open a powerful way to probe nanoparticles and understand their role in disk astrochemistry.

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Appendix

Review of Circumstellar Disk Physics

A.1. Stellar Radiation

The surface layer has energy density given by

$$ u_{\text{rad}}(r) = \left( \frac{L_*}{4\pi r^2 c} \right)^2, $$

$$ \chi = \frac{u_{\text{rad}}}{u_{\text{MMP}}} \approx 5.3 \times 10^3 \left( \frac{L_*}{L_\odot} \right) \left( \frac{100 \text{ au}}{r} \right)^2, $$

(17)

where $u_{\text{MMP}} = 8.64 \times 10^{-13}$ erg s$^{-1}$ is the typical energy density of the diffuse interstellar radiation from Mathis et al. (1983).

A.2. Disk Mass and PAH Mass

The total gas and dust mass of a disk is estimated as

$$ M_{\text{disk}} = \int_{R_{\text{in}}}^{R_{\text{out}}} dr \int dz (2\pi r \mu m_H n_H (r, z)) = \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi r \Sigma(r) dr = \frac{2\pi \Sigma_1 au^\alpha}{2 - \alpha} (R_{\text{out}}^{2 - \alpha} - R_{\text{in}}^{2 - \alpha}), $$

(18)

where $\Sigma(r) = \Sigma_1 (r/au)^{-\alpha}$ has been used. For a fiducial disk of $R_{\text{in}} = 1$ au, $R_{\text{out}} = 300$ au, and $\Sigma_1 = 1$, we get $M_{\text{disk}} \sim 0.2 M_\odot$, assuming $\alpha = 1$. The dust mass is $10^{-2} M_{\text{disk}} = 0.002 M_\odot$.

The total mass of $X$ nanoparticles (PAHs or nanosilicates) from both disk and surface layer is evaluated as

$$ M_X = \int_{R_{\text{in}}}^{R_{\text{out}}} dr \int dz (2\pi r \mu m_H) \int \frac{dm_X}{n_H da} da = \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi \Sigma_1 (r/au)^{-\alpha} dr \int \frac{dm_X}{n_H da} da,
= \int_{R_{\text{in}}}^{R_{\text{out}}} 2\pi \Sigma_1 (r/au)^{-\alpha} dr \int \frac{\rho \Sigma_1 da}{3n_H da} da,
= \frac{M_{\text{disk}} m_X b_X}{\mu m_H} \frac{M_{\text{disk}} n_p}{M_{\text{PAH}}} = \frac{M_{\text{disk}} m_X b_X}{\mu m_H}, $$

(19)

where $m_X$ is the average atomic mass of PAHs and $b_X$ is the abundance of C in nanoparticles. For graphene of purely carbon, $m_X = m_C$.

A.3. Thermal Dust Emission

In addition to spinning emission, the grains thermally heated (by starlight, etc.) in the disk emit thermal emission. The luminosity of emission from the entire disk is equal to

$$ L_\nu = 4\pi \nu \int dr (2\pi r) \int dz (\kappa_\nu B_\nu(T_r) e^{-\tau_\nu})
= 4\pi \nu \int dr (2\pi r) \int dz \tau_\nu B_\nu(T_r) e^{-\tau_\nu}, $$

(20)

where $\kappa_\nu$ is the absorption coefficient, $d\tau_\nu = \alpha_\nu dz = \kappa_\nu \rho(z, r) dz$ is the optical depth along the $z$-direction, and $\tau_\nu$ measures the optical depth from $z$ to infinity (Chiang et al. 2001). For an isothermal disk, this integral yields

$$ F_{\text{th}}(\nu) = \frac{1}{4\pi D^2} \int_{R_{\text{in}}}^{R_{\text{out}}} 4\pi B_\nu(T_r) (1 - e^{-\tau}) 2\pi rdr
= \frac{1}{4\pi D^2} \int_{R_{\text{in}}}^{R_{\text{out}}} 4\pi B_\nu(T_r) (1 - e^{-\kappa_\nu \rho(z, r) dz}) 2\pi rdr, $$

(21)

where $\tau_\nu = 0$ at the far-side surface layer.
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