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Dust growth and dust trapping in protoplanetary disks

Nienke van der Marel, Brenda Matthews

Herzberg Astronomy & Astrophysics Programs, National Research Council of Canada, Victoria, BC, Canada

Ruobing Dong

Department of Physics & Astronomy, University of Victoria, Victoria, BC, Canada

Tilman Birnstiel

University Observatory, Faculty of Physics, Ludwig-Maximilians-Universitat Munchen, Munich, Germany;

Andrea Isella

Department of Physics & Astronomy, Rice University, Houston, TX, USA;

Abstract. ALMA has revolutionized our view of protoplanetary disks, revealing structures such as gaps, rings and asymmetries that indicate dust trapping as an important mechanism in the planet formation process. However, the high resolution images have also shown that the optically thin assumption for millimeter continuum emission may not be valid and the low values of the spectral index may be related to optical depth rather than dust growth. Longer wavelength observations are essential to properly disentangle these effects. The high sensitivity and spatial resolution of the next-generation Very Large Array (ngVLA) will open up the possibilities to spatially resolve disk continuum emission at centimeter wavelengths and beyond, which allows the study of dust growth in disks in the optically thin regime and further constrain models of planet formation.

1. Introduction

The planet formation process remains one of the major puzzles in modern-day astronomy. Planets are known to form in protoplanetary disks of gas and dust around young stars (Williams & Cieza 2011). A large amount of research has been conducted in the second half of the twentieth century, but many questions remain unanswered. In particular, planet formation is hindered by a number of growth barriers, according to dust evolution theory, while observational evidence indicates that somehow these barriers must have been overcome. The core accretion process, where the accretion of dust particles and planetesimals results in solid cores of \sim Earth mass, followed by runaway gas accretion, is a promising mechanism to form the range of planets that are seen in both our Solar System and beyond (e.g. Winn & Fabrycky 2015). However, the core accre-

tion process requires the growth of planetesimals from submicron-sized dust grains that are seen in the interstellar medium (ISM). These first steps in dust growth in protoplanetary disks, where the dust evolution is governed by the drag forces between dust and gas, have proven to be one of the most challenging parts in the planet formation process (e.g. Testi et al. 2014, and references therein).

In the last two decades, clear evidence has been found for dust grain evolution in disks beyond the grain sizes in the interstellar medium, through (interferometric) millimeter observations of disks (Beckwith & Sargent 1991; Testi et al. 2003; Andrews & Williams 2005; Natta et al. 2007; Isella et al. 2009; Ricci et al. 2010, e.g.), indicating the presence of millimeter and even centimeter-sized particles in the outer regions of protoplanetary disks through multi-wavelength continuum observations and measurements of the spectral index α_{mm} (millimeter flux $F_\nu \sim \nu^{\alpha_{mm}}$). The value of α_{mm} can provide information on the particle size in protoplanetary disks (see Testi et al. 2014, and references therein). For (sub)micrometer-sized dust, such as found in the ISM (interstellar medium), α_{mm} is typically 3.5–4.0, but when dust grows to millimeter sizes, α_{mm} is expected to decrease to 2–3 (Draine 2006; Ricci et al. 2010). When the dust emission is optically thin and in the Rayleigh-Jeans regime, the observable α_{mm} can be related to the dust opacity index $\beta = \alpha - 2$, with $\beta < 1$ for millimeter grains and larger (Natta et al. 2004). Furthermore, β is related to the dust opacity of a certain dust grain size population $n(a)$ as $\kappa_\nu \propto \nu^\beta$, where β is mostly sensitive to the maximum grain size a_{\max} (Draine 2006).

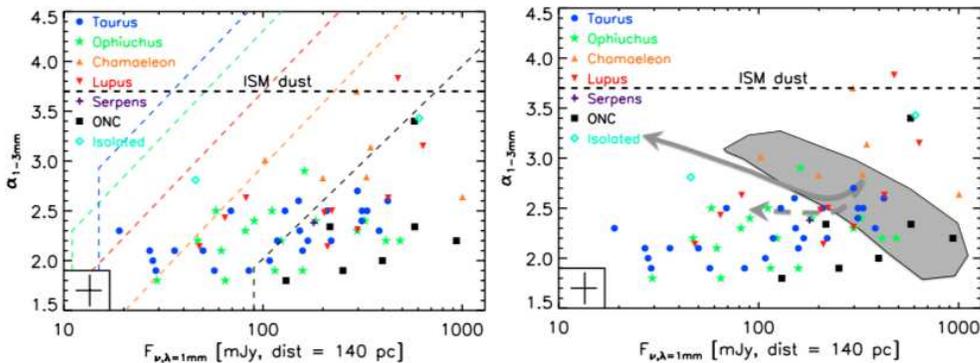


Figure 1. Spectral index α_{mm} between 1.1 and 3 mm against 1.1 mm flux for disks in various nearby star forming regions. The dashed diagonal lines (left panel) mark the sensitivity limits of the various surveys. The grey area in the right panel illustrates the predictions of dust evolution models (Birnstiel et al. 2010), and the arrows indicate the effect of dust evolution including radial drift (solid) and pressure traps (dashed) (Pinilla et al. 2012b). Figure taken from Testi et al. (2014).

Initially, grain growth in protoplanetary disks was primarily based on unresolved or marginally resolved millimeter data in surveys of star forming regions, showing α_{mm} values well below the ISM value of 3.5–4.0 (see Figure 1), indicating millimeter-sized particles in the outer disk. For a long time, it remained unclear how these particles could be present, due to the so-called *radial drift* problem, which results in a rapid inward drift of dust particles in a disk when grown to millimeter sizes (Whipple 1972; Weidenschilling 1977). For a disk with a smooth radial density profile, both the gas surface density and temperature, and thus the pressure, decrease radially outward. This

additional pressure support results in a slightly sub-Keplerian orbital velocity for the gas. In contrast, dust particles are not pressure supported and want to orbit at Keplerian speed, but as they are embedded in a sub-Keplerian gas disk, they are forced to orbit at lower speed which leads to a removal of angular momentum from the particles to the gas, causing the particles to spiral inward. The dust particles are thus experiencing a drag force by the gas, depending on its Stokes number St , which describes the coupling of the particles to the gas and depends on the dust particle size and the local gas surface density (see e.g. Brauer et al. 2008; Birnstiel et al. 2010). For small dust particles, $St \ll 1$, they are strongly coupled to the gas and do not drift inwards, but radial drift becomes significant when the particle size increases and reaches its strongest value when $St = 1$. In practice, millimeter-dust particles in the outer disk can have St values close to unity and are expected to drift inwards on time scales as short as 100 years, hence further dust growth is hindered. An additional problem is *fragmentation*: while low-velocity collisions lead to particle growth, high-velocity impacts lead to destruction according to experimental and theoretical work on dust interaction (Blum & Wurm 2000). The combination of the radial drift and fragmentation problems is also called the ‘meter-size barrier’ because a one-meter size object at 1 AU drifts efficiently inwards limiting further growth, and equivalently dust particles in the outer disk cannot grow beyond millimeter sizes.

A proposed solution to explain the presence of larger dust grains in disks as the start of planet formation, is a so-called *dust trap*, where dust particles are being ‘trapped’ in local pressure maxima in the outer disk (Whipple 1972; Klahr & Henning 1997; Rice et al. 2006; Brauer et al. 2008; Pinilla et al. 2012b). Such a pressure maximum or pressure bump can arise as a radial dust trap at the edges of dead zones (e.g. Varnière & Tagger 2006), at the edges of gas gaps cleared by planets (Zhu et al. 2012; Pinilla et al. 2012a), in zonal flows (Johansen et al. 2009; Pinilla et al. 2012b) or as azimuthal dust traps in long-lived vortices (e.g. Barge & Sommeria 1995; Klahr & Henning 1997), which can be the result of a Rossby Wave Instability of a radial pressure bump (e.g. Lovelace et al. 1999; Wolf & Klahr 2002; Lyra et al. 2009; Regály et al. 2012). Pressure maxima as a solution for dust growth beyond millimeter sizes were proposed theoretically, but without spatially resolved information on the dust grain size distribution within the disk this phenomenon remained speculative.

The *Atacama Large Millimeter/submillimeter Array* (ALMA) in Chile, which started operations in 2012, has revolutionized our view of protoplanetary disks, in particular on the existence of dust traps, starting with the discovery of the highly asymmetric millimeter-dust concentration in Oph IRS 48 (van der Marel et al. 2013). Whereas the gas and micrometer-dust are distributed along a ring the millimeter emission showed evidence for dust trapping in a vortex, thought to be generated by a Rossby Wave Instability of a radial pressure bump. Follow-up observations at centimeter wavelengths with the VLA confirmed that the azimuthal width of the dust trap decreased with wavelength (van der Marel et al. 2015a), as predicted by dust trapping models (e.g. Birnstiel et al. 2013). Oph IRS 48 is a so-called transitional disk, a disk with a cleared inner dust cavity (e.g. Espaillat et al. 2014, and references therein), which were of particular interest in dust evolution predictions for keeping millimeter-sized dust grains in the outer disk (Pinilla et al. 2012a). Other transition disks imaged with ALMA show a range of azimuthally symmetric and asymmetric dust rings (Casassus et al. 2013; Zhang et al. 2014; Pérez et al. 2014; van der Marel et al. 2015b; Pinilla et al. 2017), confirming their ring-like morphologies as seen with previous interferometers such as CARMA and the SMA (e.g. Brown et al. 2009; Isella et al. 2010; Andrews et al. 2011). The

existence of radial dust traps was primarily indicated by the difference in distribution of the gas (as traced by CO isotopologues) and millimeter dust (e.g. Bruderer et al. 2014; Perez et al. 2015; van der Marel et al. 2016; Dong et al. 2017; Fedele et al. 2017) and the difference with the micrometer-sized dust grains (Garufi et al. 2013; Pinilla et al. 2015). Multi-wavelength ALMA observations between 1.3 and 0.45 millimeter provided a hint of radial trapping in the SR 21 and SR 24S disks through spatially resolved $\alpha(r)$ which decreased to <3 in the ring emission (Pinilla et al. 2015, 2017), and azimuthal changes in α_{mm} were seen in the asymmetries in HD 142527 (Casassus et al. 2015) and HD 135344B (Cazzoletti et al. 2018). Combining ALMA with VLA data at centimeter wavelengths results in further evidence for dust trapping in MWC 758 (e.g. Marino et al. 2015), but the low spatial resolution and sensitivity limits the calculation of a spatially resolved $\alpha_{mm}(r)$ map.

Another spectacular ALMA result in this context is the imaging of disks at ultra high angular resolution of ~ 20 mas or a few AU at the distance of nearby star forming regions. The mind-blowing image of HL Tau (ALMA Partnership et al. 2015) of the ALMA Long Baseline Campaign has revealed that even dust disks without inner cavity may exist of ring-like structures, which a remarkable similarity to the predictions of Pinilla et al. (2012b) of local pressure maxima that are required for the explanation of millimeter-sized dust in the outer disk. The HL Tau image was quickly followed by other multi-ring disks, such as TW Hya (Andrews et al. 2016) and HD 163296 (Isella et al. 2016). Explanations for the dust rings range from planets carving gaps (Lin & Papaloizou 1979), snow lines (Zhang et al. 2015), sintering (Okuzumi et al. 2016) and secular gravitational instabilities (Takahashi & Inutsuka 2016). If the dust rings are indeed caused by planets, trapping is expected to occur. Multi-wavelength observations indeed reveal radial variations of α_{mm} along the gaps and rings in HL Tau and TW Hya (Carrasco-González et al. 2016; Tsukagoshi et al. 2016), but the evidence is still marginal with the currently available data. On the other hand, evidence for radial drift is evident in observations. SMA observations already revealed evidence for a segregation between the dust and gas in the IM Lup disk (Panić & Hogerheijde 2009), with the gas outer radius being twice as large as that of the dust. Multi-wavelength continuum observations show a decrease of particle grain size with radius for a number of primordial disks (Pérez et al. 2015; Tazzari et al. 2016; Tripathi et al. 2018). Clearly, in lack of one or more dust traps in the outer disk, dust particles do drift inwards to the nearest pressure maximum. On the other hand, this implies that any extended dust disk must in fact consist of one or more pressure bumps, to keep the dust particles away from the center of the disk.

2. The optical depth problem

The results described above appear very promising in explaining the presence of large dust grains in protoplanetary disks as the start of the planet formation process, but they suffer from a major problem: the spectral index α_{mm} can only be related to β in a simple linear fashion for optically thin emission. The optical depth $\tau_\nu(r)$ is defined as

$$\tau_\nu(r) = \int_{-\infty}^{\infty} \rho \kappa_\nu ds = \frac{\kappa_\nu \Sigma(r)}{\cos i} \quad (1)$$

with $\Sigma(r)$ the dust surface density at radius r and i the inclination and the emitted flux F_ν integrated over a disk area can be computed as:

$$F_\nu = \frac{\cos i}{d^2} \int B_\nu(T(r))(1 - e^{-\tau_\nu(r)})2\pi r dr \quad (2)$$

with distance d , Planck function B at temperature T , which reduces to $F_\nu \propto B_\nu(T) \propto \nu^2$ for optically thick emission and $F_\nu \propto \kappa_\nu B_\nu(T) \propto \nu^{2+\beta}$ for optically thin emission ($\tau_\nu \ll 1$). This immediately illustrates that the spectral index α_{mm} is 2 (and thus $\beta \sim 0$) for optically thick emission regardless of the grain size, and a low value of β does not automatically imply large dust grains. The optical depth is generally estimated by comparing the measured brightness temperature T_b ($T_b \sim I_\nu = \frac{F_\nu}{d\Omega}$) with the solid angle $d\Omega$ and the physical dust temperature T_{dust} as calculated from a radiative transfer model. Typical disk observations of millimeter interferometry do show lower values for T_b than T_{dust} , indicating $\tau_\nu \sim 0.5$ or lower, but if the optically thick emission is concentrated on size scales smaller than the resolution, optical depth effects cannot be ruled out as an explanation for the low β values based on millimeter emission (Ricci et al. 2012; Tripathi et al. 2017). This is generally measured using the filling factor f , the fraction of the disk area which is optically thick. Thus, the evidence for dust growth and dust trapping based on spectral index values from millimeter observations may not be reliable. Furthermore, if the assumption of optically thin dust emission is no longer valid, this also has potentially large consequences for disk dust mass estimates, which are generally taken as a linear relation between M_{dust} and integrated millimeter flux F_ν as:

$$M_{\text{dust}} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T)} \quad (3)$$

If the dust emission is optically thick, the derived disk dust mass is only a lower limit. Even in high resolution ALMA observations, the millimeter disk emission often remains unresolved (e.g. in $>30\%$ of the disks in the Lupus survey which has a spatial resolution of $0.25''$ or 20 AU radius, Ansdell et al. (2018)), implying that the majority of disks are much smaller than previously thought, and their emission is potentially optically thick. However, even for partially resolved extended disks the integrated flux may be dominated by optically thick emission from either rings or from the inner part of the disk where the dust concentrates as a result of radial drift in absence of pressure maxima in the outer disk (Tripathi et al. 2018). The high spatial resolution of ALMA is a crucial factor here as high resolution observations have demonstrated that dust emission is concentrated in much narrower rings than previously thought.

3. The role of the next-generation VLA

In order to study dust growth in protoplanetary disks, spatially resolved multi-wavelength observations in the optically thin regime are crucial. The next-generation Very Large Array (ngVLA) offers high angular resolution (~ 10 mas) at long wavelengths (17-93 GHz or 3-18 mm) where $\tau_\nu \ll 1$. The sensitivity ($\sim 0.3\mu\text{Jy}/\text{beam}$ for 1 hour integration at 40 GHz) allows quality observations at high signal-to-noise, resulting in clear images of the structures in disks. The current VLA does not have the resolution or sensitivity to achieve this result in a reasonable amount of time. Of particular importance for dust growth studies is the spatially resolved spectral index β_{cm} which can be calculated

across optically thin wavelengths. This opens up a large range of possibilities to answer questions on the origins and mechanisms of the structures in disks observed by ALMA.

3.1. Azimuthal asymmetries

The azimuthal asymmetries, though to be dust trapping vortices, have gained a large interest from the community, but a lot of questions regarding their origin remain unclear. A spatially resolved $\beta_{cm}(r, \phi)$ can help to disentangle azimuthal trapping from other proposed effects to explain dust asymmetries such as eccentricities (Ataiee et al. 2014; Ragusa et al. 2017), as eccentric disks would not show an azimuthal dependence of β_{cm} . Furthermore, the measurement of $\beta_{cm}(r, \phi)$ can constrain the trapping efficiency in the disk, and in combination with estimates of the gas surface density, lead to independent constraints on the viscosity and turbulence (Birnstiel et al. 2013; Lyra & Lin 2013), which tends to diffuse the dust in the vortex. Quantitative estimates of the turbulence can further be used to estimate the time scales of dust trapping in a vortex and relate them to their observability. For AB Aur, Fuente et al. (2017) claim a decaying vortex due to the azimuthal extended emission at longer wavelengths (in contrast to dust trapping predictions), but optical depth effects need to be excluded to confirm this claim.

Another interesting consequence of trapping in a vortex is a size segregation due to the vortex’s self-gravity: whereas smaller grains will be trapped in the center of the vortex, larger grains are expected to be trapped *ahead* in the azimuthal direction (Baruteau & Zhu 2016): a shift was indeed observed in the asymmetry in HD 135344B in ALMA observations, but in the opposite direction (Cazzoletti et al. 2018). In order to rule out any effects due to optically thick emission, ngVLA observations at similar angular resolution, can test the predictions of Baruteau & Zhu (2016) in a large number of disks.

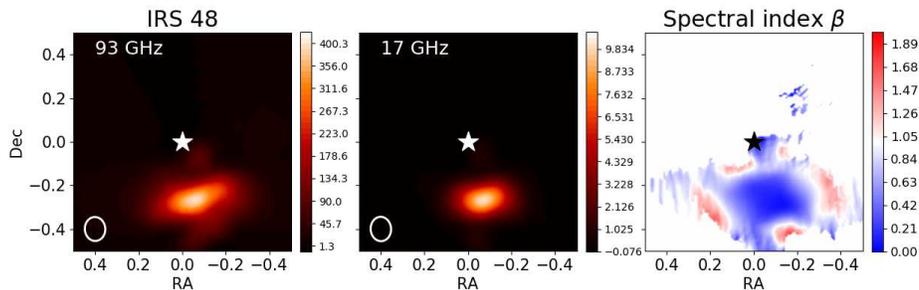


Figure 2. Simulated images of the spectral index $\beta(r, \phi)$ for the azimuthal asymmetry in Oph IRS 48 at centimeter wavelengths, as expected from ngVLA observations at 97 and 17 GHz in a 2 hour integration. Flux units are given in $\mu\text{Jy}/\text{beam}$. Oph IRS 48 is expected to show a decrease of β in the center due to dust growth.

As a demonstration, we have created intensity profiles of a highly asymmetric disks (Oph IRS 48) based on its observed morphology with ALMA and VLA and scaled to their expected centimeter flux at 97 and 17 GHz. In Figure 2 we demonstrate that the

spatially resolved β_{cm} as calculated from 3 and 18 millimeter emission can be measured with an accuracy of ~ 0.1 in high SNR observations with the ngVLA in 2 hours per setting, using the CASA simulator and the ngVLA configuration.

3.2. Multi-ring disks

Spatially resolving the multi-ring systems such as HL Tau in multiple centimeter wavelengths will help to constrain their origin, which is currently completely unclear: cleared gaps by planets is a tempting explanation, but this requires (giant) planets at tens or even hundreds of AU away from the star, which are very rare in exoplanet demographics (Winn & Fabrycky 2015; Bowler 2016) and difficult to explain in reasonable time scales in planet formation theory (Helled et al. 2014). The edges of planet gaps are pressure maxima where dust is expected to be trapped; a measure of $\beta_{cm}(r)$ can immediately tell if the rings are consistent with dust traps. If not, other explanations for the origin of the rings will need to be considered.

3.3. Radial drift

In disks without pressure maxima in the outer disk, the larger dust particles are expected to drift inwards and form a sharp outer continuum edge (Birnstiel & Andrews 2014). Although this effect has been demonstrated through comparison between the millimeter dust emission and the much more extended distribution of the gas as traced by the CO (e.g. Panić & Hogerheijde 2009; Andrews et al. 2012; de Gregorio-Monsalvo et al. 2013; Ansdell et al. 2018), a quantification of the drift and associated time scales remain unexplored due to the uncertainties introduced by the high optical depth in the inner part of the dust disk (e.g. Pérez et al. 2015; Tazzari et al. 2016; Tripathi et al. 2018). Measuring $\beta_{cm}(r)$ in optically thin wavelengths will set better constraints on the grain size distribution within the disk and will help to constrain dust evolution models in providing better estimates for e.g. drift time scales and fragmentation.

3.4. Disk masses

Disk dust masses are generally derived from disk-integrated millimeter fluxes using the assumption of optically thin emission, but it is quite likely that this assumption is not valid, implying that many of the derived disk masses (usually calculated with the dust mass and a gas-to-dust ratio of 100) are lower limits. This has important consequences for our understanding of the dynamics in disks: gravitational instability (Boss 1997) may occur for disk masses $>10\%$ of the stellar mass, which is generally well above our current estimates of the disk mass. However, if large amounts of the millimeter emission is optically thick, these disk masses are severely underestimated and gravitational instabilities could be important for disk fragmentation, dynamics and giant planet formation than currently thought. Large disk surveys with the ngVLA of nearby star forming regions can provide us with flux measurements of hundreds of disks, similar to current ALMA surveys. The sensitivity of the Lupus ALMA disk survey ($\sim 0.3M_{\text{Earth}}$ as 3σ detection limit Ansdell et al. 2018) can be reached in 2 minutes per source with the ngVLA at 40 GHz, allowing full snapshot surveys in only a few hours.

4. Conclusions

Whereas ALMA has revolutionized our understanding of protoplanetary disks by revealing a large diversity of structures indicating concentrated dust growth, a better understanding and quantification of the dust growth processes can only be achieved with longer wavelength observations in the centimeter regime where the dust becomes optically thin, in particular through spectral index observations. Using the Square Kilometre Array (SKA) to derive dust spectral indices using even longer wavelengths (>5 cm) is impractical, as the dust emission becomes too faint to be detected at high spatial resolution. The ngVLA provides unprecedented possibilities to study dust growth in disks and further explore the dust trapping process.

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