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Note

Evidence for pebbles in comets

K.A. Kretke *, H.F. Levison

Southwest Research Institute, 1050 Walnut Ave., Suite 300, Boulder, CO 80302, USA

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ABSTRACT

When the EPOXI spacecraft flew by Comet 103P/Hartley 2, it observed large particles floating around the comet nucleus. These particles are likely low-density, centimeter- to decimeter-sized clumps of ice and dust. While the origin of these objects remains somewhat mysterious, it is possible that they are giving us important information about the earliest stages of our Solar System's formation. Recent advancements in planet formation theory suggest that planetesimals (or cometesimals) may grow directly from the gravitational collapse of aerodynamically concentrated small particles, often referred to as "pebbles." Here we show that the particles observed in the coma of 103P are consistent with the sizes of pebbles expected to efficiently form planetesimals in the region that this comet likely formed, while smaller pebbles are may be expected in the majority of comets, whose chemistry is often indicative of formation in the colder, outer regions of the protoplanetary disk.

1. Introduction

When the Epoxi spacecraft flew by Comet 103P/Hartley 2 it observed large particles floating around the comet's nucleus (A'Hearn et al., 2011). Based on best estimates of the albedo of these objects, they appear to have a rather steep size distribution in which the largest particles are thought to be ~10 cm in size (Kelley et al., 2013; Harmon et al., 2004). These particles are larger than has been generally detected in the coma of other comets. While it is possible that the size of these particles is determined simply by the erosive process inside the comet (Meech and Svoren, 2004), another intriguing possibility is that these particles may be left over relics of the formation process.

In the past it has generally been assumed that the icy bodies in the outer Solar System were all built up in a hierarchical fashion. In this picture, km-sized comets are built from binary collisions of smaller bodies, while the larger Kuiper belt objects and even the cores of the giant planets were formed by accretion of these small "cometesimals" (Stern, 1996; Stern and Colwell, 1997; Kenyon, 2002; Kenyon et al., 2008). However, there are important challenges in forming comets via this mechanism. First, it may not be possible to grow to binary collisions up to km-sized objects. As particles grow their sticking efficiency is reduced, possibly leading to a regime in which collisions are more likely to lead to "bouncing" rather than accretion (Zsom et al., 2010; Güttler et al., 2010). Additionally, as small micron sized particles grow into macroscopic mm to m-sized particles they attain larger relative velocities, increasing the likelihood that collisions will be destructive (Blum and Wurm, 2000, 2008). And while mass-transfer precesses may allow lucky particles to grow beyond these barriers, the timescale for formation of planetesimals becomes long enough to become problematic for subsequent planet formation (Windmark et al., 2012). Additionally, even if these barriers can be overcome and planetesimals can be formed, to grow the larger Kuiper belt objects in the time allotted by this process the disk must have been extremely dynamically cold and 100–1000 times more massive than it is today (Kenyon et al., 2008).

However, more recently there have been theoretical and observational reasons to suggest that instead of forming in this bottom up manner, planetesimals may form directly by the gravitational collapse of a dense cloud of small particle embedded in the protoplanetary disk (the gravitational instability or GI hypothesis). In particular, recent breakthroughs in theory and computer simulation have demonstrated that under reasonable conditions particles can be concentrated to the point that they will gravitationally collapse, as suggested by the GI hypothesis (see reviews by Chiang and Youdin, 2010; Johansen et al., 2014). In these models particles that are small enough to have their orbits strongly perturbed by aerodynamic drag, yet large enough to still be decoupled from the gas (mm to m sized objects depending on the gas disk properties) can self-clump, forming gravitationally bound objects of 10–1000 km in size (e.g. Johansen et al., 2007, 2015).

Furthermore, new observational signatures may support the idea that planetesimals form via GI rather than through hierarchical growth. For example, the size distribution of planetesimals in the asteroid belt appears to be inconsistent with the predictions of classical planetesimal collisions, and instead may be showing us that the larger asteroids had to directly form as relatively large objects (Morbidelli et al. (2009), although see Weidenschilling (2011) for an alternative interpretation). Additionally, the delicate wide binaries in the Kuiper Belt are unlikely to be made by normal processes such as collisions or binary exchanges, instead they are most easily made by a collapsing, fragmenting gravitationally bound pebble "cloud" (Nesvorný et al., 2010; Parker et al., 2011). Furthermore, if one combines the observed activity of comets with the strength the dusty surface layers of comets, the dust on cometary surfaces must be in the form of relatively large particles in order for water sublimation to power cometary activity (Skorov and Blum, 2012; Blum et al., 2014). All of various lines of evidence combined paint a consistent picture in which small icy bodies in the outer-Solar System formed from collapsing clouds of small "pebbles".

If Kuiper belt objects did indeed form from the gravitational collapse of clouds of small pebbles, there may be signatures of these formative pebbles extant in comets today. While some pebbles may destructively fragment during the planetesimal formation process, so long as the initially formed planetesimal was under 100 km in radius it is expected that most of the pebbles are unlikely to collide at high enough speed to cause fragmentation (Wahlberg Jansson and Johansen, 2014). Additionally, while thermal processing will alter the cometary surface, creating lag deposits that mask the underlying structure of the comet, only the surface layers of the comet likely have been significantly altered by thermal processing (Mumma et al., 1993). This may leave pristine material beneath the lag layer. With this in mind, in this *Note* we are interested in investigating the speculative proposition that the large particles observed in the coma of Hartley 2 may be remnants of the initial pebbles which formed the comet. To this end we will address the issue of

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* Corresponding author.

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the expected size of pebbles in different regions of the protoplanetary disk and the possibility of predictable trends.

In this paper we look at the large particles in the coma of comet Hartley 2 and show that their sizes are consistent with the size of pebbles expected to efficiently form planetesimals. In Section 2 we describe from a theoretical standpoint how large pebbles need to be in protoplanetary disks to be concentrated by well-understood processes. In Section 3 we use the chemical composition of comet Hartley 2 to estimate its formation location so that we can place the sizes of the particles in it coma in context with the theoretical expectations. Finally, in Section 4 we summarize our results and discuss the implications and what future data may help further elucidate the formation mechanism of comets.

2. Theoretical expectations of pebble sizes

There are three main ideas for how pebbles can be concentrated to the degree necessary for gravitational collapse in protoplanetary disks, turbulent eddies, pressure bumps and vortices, and the streaming instability (see Johansen et al., 2014, for a review). Each of these processes will only work on particles within a limited range of sizes, determined by the particles' Stokes numbers (τ). The Stokes number is defined as $\tau \equiv t_s \Omega$, where t_s is the stopping time of the particle due to aerodynamic drag and $\Omega \equiv \sqrt{GM_*/r^3}$ is the Keplerian orbital frequency around a star of mass M_* at a heliocentric distance r. The stopping time is

$$t_s = \begin{cases} \frac{a\rho_s}{c_s\rho_g}, & \text{if } a < \frac{3}{2}\lambda \\ \frac{2a^2\rho_s}{3c_s\rho_g}, & \text{otherwise} \end{cases} \qquad (1)$$

(Adachi et al., 1976) where λ is the gas mean-free-path, c_s is the sound-speed, ρ_s is the density of the solid particle, and ρ_g is the local gas density.

Turbulent eddies should concentrate particles whose stopping times are comparable to the eddy turnover times, which corresponds roughly to $\tau \sim 10^{-5} - 10^{-4}$ in typical protoplantary disks (e.g. Cuzzi et al., 2008, 2010), however Pan et al. (2011) found that strong clustering of particles in this size range may be too difficult to form the number of required planetesimals. Particle concentration in pressure bumps (e.g. Whipple, 1972; Haghighipour and Boss, 2003; Kretke et al., 2009), and vortices (e.g. Barge and Sommeria, 1995; Lyra et al., 2008) is most effective for particles with $\tau \sim 1$. The streaming instability (Youdin and Goodman, 2005; Johansen et al., 2007) was shown to effectively concentrate particles with τ in the range of between 10^{-2} and 1 (Bai and Stone, 2010; Carrera et al., 2015). As the streaming instability is a linear instability that has been robustly shown to function under physically reasonable conditions, for the remainder of this paper we will take the streaming instability range as the size scale of interest.

To determine the sizes of particles susceptible to the streaming instability, we must know the midplane gas density and temperature profiles in protoplanetary disks. Unfortunately, these parameters cannot currently be measured directly in the regions where comets are thought to have been formed (~5 to ~50 AU), and theoretically depend upon parameters that are expected to vary over the disk lifetime (such as the mass-accretion rate through the disk) and/or are generally poorly constrained (such as the grain opacity and the disk viscosity). However, we can construct a reasonable fiducial model based upon existing constraints and discuss how our results are sensitive to our assumptions.

For the protoplanetary disk structure we assume a disk heated by a combination of viscous heating and stellar irradiation. We use the models of Bitsch et al. (2015), which utilize a full radiative transfer model to calculate the 2D thermal structure of an axisymmetric protoplanetary disk. This model has the advantage of more accurately calculating the temperature profiles than more standard 1 + 1d or 2 layer calculations (e.g. Chiang et al., 2001; D'Alessio et al., 2005; Kretke and Lin, 2010), particularly in regions that may be self-shielding.

The green curves in Fig. 1 show the surface density and temperature profile for our fiducial disk model. It has a mass accretion rate of $\dot{M} = 10^{-8} M_\odot\ \mathrm{yr}^{-1}$ around a 1 Myr old star. The disk has a viscosity $\nu = \alpha c_s^2 \Omega^{-1}$ where $\alpha = 5.4 \times 10^{-3}$. We note that Bitsch et al. (2015) assume a steady-state accretion profile throughout the disk. This means that the gas surface density, Σ, is directly determined by the mass accretion rate and viscosity by $\dot{M} = 3\pi\nu\Sigma$ (Pringle, 1981). The other solid curves in Fig. 1 show how the surface density and temperature depend on the mass-accretion rate. As accretion disks are expected to lose mass over time, these higher (5×10^{-8} $M_\odot\ \mathrm{yr}^{-1}$) and lower ($5 \times 10^{-9}$ $M_\odot\ \mathrm{yr}^{-1}$) mass accretion rates can be thought of as earlier and later evolutionary stages of the disk, respectively.

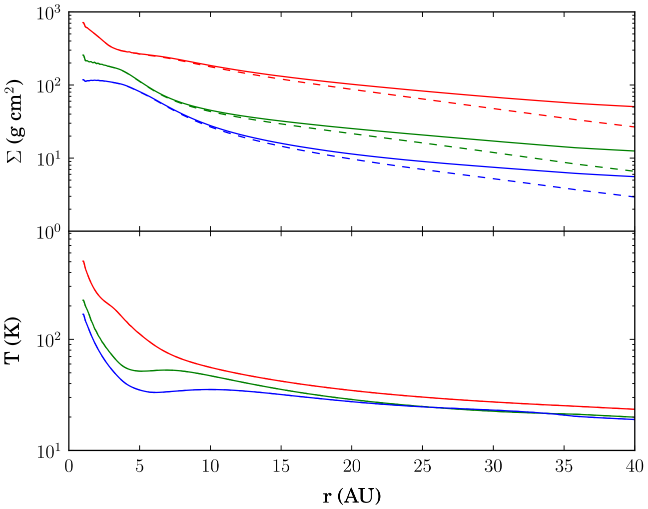

Fig. 1. The disk surface density (upper panel) and temperature (lower panel) profiles assumed in this paper. The disks have mass accretion rates of 5×10^{-8}, 10^{-8} (fiducial), and 5×10^{-9} $M_\odot\ \mathrm{yr}^{-1}$ in red, green and blue, respectively. The dashed-curves indicates how we modify the surface density to account for an exponential fall off as described in Eq. (2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

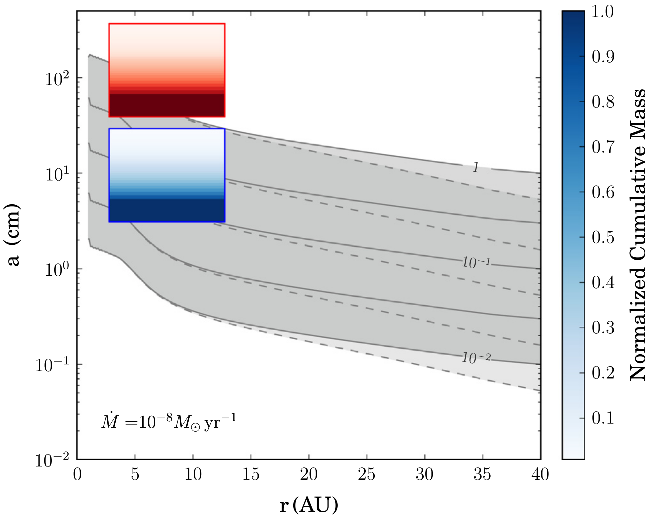

Fig. 2. The gray shaded region indicates the size range of particles with density $\rho_s = 0.5\ \mathrm{g\ cm}^{-3}$ susceptible to concentration via the streaming instability in the nominal disk. The black curves indicate curves of constant τ, of 1, 0.3, 10^{-1}, 3×10^{-2}, 10^{-2}. The dashed curves indicate how the τ values would change if we modify the surface density by adding an exponential cutoff as in Eq. (2). The color gradients within the blue and red boxes indicate the range of sizes of particles observed in the coma of Comet Hartley 2 if a bright or dark albedo is assumed, respectively. The shading corresponds to the normalized fraction of the pebble mass in each size bin. The boxes are placed at a temperature range consistent with the comet's chemistry as described in Section 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This steady-state assumption is expected for the inner region of any viscously evolving disk (Pringle, 1981). However, real disks do not extend forever, and as one enters into the outer region of the disk viscous evolution will lead to a smooth decrease in the disk surface density. Observations of disks suggest that an exponential cut-off is an appropriate approximation for the outer disk surface density profile (Andrews et al., 2010). This cutoff will modify the surface density of the disk significantly, but it will only make minor changes to the disk temperature profile. That is because the thermal structure of the outer region of the protoplanetary disk is dominated by the passive re-radiation of the intercepted stellar light, a process with only very weak dependencies on the disk surface density. Therefore we approximate the disk parameters in a disk with an exponential cutoff as the dashed curves in Fig. 1, where the surface density is

$$\Sigma = \frac{\dot{M}}{3\pi\nu} \exp\left(\frac{-r}{50\ \mathrm{AU}}\right). \qquad (2)$$

and we assume the temperature profile of this disk is unchanged.

In Fig. 2 we show the sizes of such pebbles in our fiducial disk, assuming $\rho_s = 0.5\ \mathrm{g\ cm}^{-3}$. The solid curves show the size of particles with a fixed τ (ranging from 10^{-2} to 1) in our fiducial disk with $\dot{M} = 10^{-8} M_\odot\ \mathrm{yr}^{-1}$. This range of τ is the size range most susceptible to the streaming instability, so we highlight it with gray shading. The dashed-curves (and light gray region) shows how the Stokes numbers would vary in the disk if we modify our fiducial disk by assuming an exponential