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.

Keywords: Comets, origin, Comets, coma, Planet Formation

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 alloted by this process the disk must have been extremely dynamically cold and 100 to 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 (nm 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; Johansen et al., 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” (Nesvorny 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”. 

2
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 (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 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 its 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 ($\tau$). 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 $\Omega \equiv \sqrt{GM_s/r^3}$ is the Keplerian orbital frequency around a star of mass $M_s$ at a heliocentric distance $r$. The stopping time is

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

(1)
where $\lambda$ is the gas mean-free-path, $c_s$ is the sound-speed, $\rho_s$ is the density of the solid particle, and $\rho_g$ 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 protoplanetary disks (e.g. Cuzzi et al., 2008; Cuzzi et al., 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 (Whipple, 1972; Haghighipour and Boss, 2003; Kretke et al., 2009, e.g.), and vortices (Barge and Sommeria, 1995; Lyra et al., 2008, e.g.) 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 $\tau$ 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 figure 1 show the surface density and temperature profile for our fiducial disk model. It has a mass accretion rate of $\dot{M} = 10^{-8} M_\odot yr^{-1}$ 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, $\Sigma$, is directly determined by the mass accretion rate and viscosity by $\dot{M} = 3 \pi \nu \Sigma$ (Pringle, 1981). The other solid curves in figure 1 show how the surface density and temperature depend on the mass-accretion
Figure 1. The disk surface density (upper panel) and temperature (lower panel) profiles assumed in this paper. The disks have mass accretion rates of $5 \times 10^{-8}$, $10^{-8}$ (fiducial), and $5 \times 10^{-9}$ $M_{\odot}$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.
rate. As accretion disks are expected to lose mass over time, these higher \( (5 \times 10^{-8} \, M_{\odot} \, \text{yr}^{-1}) \) and lower \( (5 \times 10^{-9} \, M_{\odot} \, \text{yr}^{-1}) \) mass accretion rates can be thought of as earlier and later evolutionary stages of the disk, respectively.

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 figure 1, where the surface density is

\[
\Sigma = \frac{\dot{M}}{3\pi\nu} \exp\left(-\frac{r}{50 \, \text{AU}}\right),
\]

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

In figure 2 we show the sizes of such pebbles in our fiducial disk, assuming \( \rho_s = 0.5 \, \text{g cm}^{-3} \). The solid curves show the size of particles with a fixed \( \tau \) (ranging from \( 10^{-2} \) to 1) in our fiducial disk with \( \dot{M} = 10^{-8} \, M_{\odot} \, \text{yr}^{-1} \). This range of \( \tau \) 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 cutoff. This figure demonstrates how the size of “pebbles” decreases with heliocentric distance in normal protoplanetary disks. The sizes of those “pebbles” is sensitive to the disk properties. In figure 3 we highlight the same range of \( \tau \) in disks with higher \( (5 \times 10^{-8} \, M_{\odot} \, \text{yr}^{-1}) \) and lower \( (5 \times 10^{-9} \, M_{\odot} \, \text{yr}^{-1}) \) mass accretion rates, corresponds to earlier and later evolutionary stages of the disk, respectively. From figure 1 we can see that the largest difference between these disks is the change in the surface density, however, at any given time, larger pebble are expected to be incorporated into comets in the inner disk as compared to the outer disk.

3. “Pebbles” in Hartley 2

In order to determine the aerodynamic properties of these pebbles, one must know three things: the size and density of the pebbles, the properties of the gaseous protoplanetary disk, and the location in the disk where the comet formed.
Kelley et al. (2013) calculated the size of the particles in the coma based on the observations of individual particles. They found that the maximum particle radius of 30 cm if one assumes a bright, icy albedo ($A_p = 0.67$) and a maximum radius of 4 m if one assumed a dark, cometary albedo ($A_p = 0.049$), with a steep size distribution of $dn/da \propto a^{-4.7}$ down to the detection limit. Kelley et al. take the dark solution to be unlikely for a number of reasons. First, if the particles are dark then the largest particles in the size distribution are 8 meters in diameter, which likely should have been resolvable. Additionally, the dark model implies that the coma consists of 0.6-14\% of the mass of the nucleus, which likely violates the constraints on the amount of mass lost each orbit (Thomas et al., 2013). Furthermore, there is substantial amount of water vapor emitted isotropically around the coma, consistent with water sublimation from large particles in the coma. However, we will include the dark solution for completeness and it may be considered an extreme upper limit on the particle sizes.

We note that due to the long estimated lifetimes (Beer et al., 2006) of these ice balls and relatively high velocity of these particles (Hermalyn et al., 2013), they likely did not sublimate enough to significantly change their size between the time of ejection and detection. Therefore we assume the observed size distribution is the same as the size distribution at launch. Additionally, while the turn-over size is not directly observed, the presence of a turn over near the detection limit can be inferred in the data because otherwise unresolved particles would cause a diffuse emission that would have been detected (see Kelley et al., 2013 for details). Therefore in our plots we assume that the differential particle size distribution is flat between the detection limit ($10^{-12}$ W m$^{-2}$ $\mu$m$^{-1}$) and a factor of two below the detection limit. This leads to most of the mass of the pebbles having sizes of either 3 to 5 cm or 40 to 60 cm assuming a bright or dark albedo, respectively.

It is extremely difficult to determine the formation location of any comet. Comet 103P is a Jupiter family comet (JFC), and from the inclination distribution of this population it is clear that the most likely immediate source region of these comets is the Kuiper Belt region ($R > 30$ AU, Mumma et al., 1993). However, modern models of solar system evolution predict that there was significant dynamical mixing early on (Levison et al., 2008) so that planetesimals from the giant planet forming region (5-14 AU) were scattered both into the Oort cloud and the scattered disk, some of which later evolved on to JFC orbits. Indeed, the varied composition of JFCs (such as the wide range of D/H ratios (Hartogh et al., 2011; Altwegg et al., 2015)) supports the idea of mixing.

Fortunately, we have additional constraints on the formation location of this comet—its composition. Comet 103P has a D/H ratio of $1.4 \times 10^{-4}$, similar to that
Figure 2. The gray shaded region indicates the size range of particles with density $\rho_s = 0.5 \text{ g cm}^{-3}$ susceptible to concentration via the streaming instability in the nominal disk. The black curves indicate curves of constant $\tau$, of $1$, $0.3$, $10^{-1}$, $3 \times 10^{-2}$, $10^{-2}$. The dashed curves indicate how the $\tau$ 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 Sec. 3.

of the Earth ([Hartogh et al., 2011]). This make it seem reasonable that comet 103P formed closer to the sun than most other well studied comets that have higher D/H ratios ([Delsemme, 1998]). Additionally, comet 103P also has a notably high CO$_2$/CO ratio of around 100:1, compared to the 1:1 or less more typical of other comets which have a high enough CO$_2$ ratio to be observed, suggesting that it may have formed significantly interior to the CO snow line. This is again in contrast to most well-characterized comets ([A’Hearn et al., 2012]). We would like to use this large CO$_2$/CO
ratio to give precise constraints on the comet’s formation location. Unfortunately, the exact pathway for CO\textsubscript{2} formation in comets is still not well understood, and different mechanisms give rise to different formation locations for 103P (e.g. Garrod and Pauly, 2011; Noble et al., 2011). One possibility is that the comet formed near or just outside of the CO\textsubscript{2} snow line (at a formation temperature around 42-52K) (Öberg et al., 2011). However, CO\textsubscript{2} is not prevalent in the gas phase, so direct condensation of CO\textsubscript{2} may not actually be that efficient at producing CO\textsubscript{2} ice. Therefore, another possible pathway for CO\textsubscript{2} ice production is by the conversion of CO trapped in amorphous water ice. This process has been demonstrated to be efficient even up to 77 K (Yokochi et al., 2012). Therefore, we will take the stance that the high CO\textsubscript{2}/CO suggests that the comet most likely formed in a region of the protoplanetary disk with a temperature between 80 and 40 K. We note that these temperatures are warmer than the spin temperature of water measured in Hartley 2 (Kawakita et al., 2004), however, that ratio may be modified by the desorption process, therefore may not be reliable indicator of formation location (van Dishoeck et al., 2014).

In figure 2 we overlay the size distribution of particles observed in the coma of Hartley 2 at the range of temperatures we believe this comet likely formed, between 80 and 40 K. With the preferred “bright” albedo, we find the particles would be consistent with a \(\tau\) range from \(2 \times 10^{-2}\) to 1, consistent with expectations for the streaming instability. If the “dark” solution turns out to be correct, then the largest particles in the coma are would likely have been larger than \(\tau = 1\), and thus is it not understood how particles of that size could have formed planetesimals. The majority of the mass is still in the expected range (particularly if the comet formed relatively close to the sun) so these large particles could be aggregates of primordial pebbles, but more detailed consideration would likely be necessary. While the Stokes number of pebbles is dependent on the disk properties, for our high and low mass-accretion rate disk models in figure 3 the bright pebbles still agree quite well with what is needed for the streaming instability.

If we assume that comets that formed farther from the sun have a similar range in \(\tau\) to theses pebbles, then they would have a maximum pebble size of \(\sim 5\) cm, but, if the size distribution is similar to that of Hartley 2, most of the mass would be in smaller, sub-centimeter sizes. Radar depolarization has indicated that there must be a significant population of coma grains larger than 2 cm in size in comet C/2001 A2 (LINEAR) (Nolan et al., 2006). The spin temperature of this comet is colder than that of Hartley 2 (Kawakita et al., 2004; Dello Russo et al., 2005), but unfortunately there is neither a D/H ratio nor a CO/CO\textsubscript{2} ratio to narrow down the formation location. In general, most comets do not have signatures of such large particles.
Figure 3. The size range of particles susceptible to concentration via the streaming instability in a high-mass accretion rate on the left, with a low-mass accretion rate on the right. The curves and gradients are similar to those in Figure 2.
There are a few exceptions. For instance Reach et al. (2000) found particles as large as 5 cm in the tail of comet Encke a comet which does have detectable CO$_2$ (Reach et al., 2013), but does not have detectable CO, although it is not clear how significant thermal processing may be obscuring the chemical composition (Fernández et al., 2005). Additionally, other detections of large particles consist of mm or up to cm sizes (e.g. Harmon et al., 2004; Trigo-Rodríguez et al., 2008, 2010). This general lack of very large particles appears consistent with the idea that these comets (which more likely formed in the outer regions of the Solar System due to the D/H and CO/CO$_2$ ratios) should have been formed from smaller pebbles.

4. Conclusions and Discussion

Comet Hartley 2 is observationally a bit of an outlier in two different and seemingly unrelated facets: it both is the comet with the largest particles observed in its coma and it has chemistry indicating that it formed at a warmer location than typical comets. Given that current theoretical models suggest that comets may have formed from the accretion of “pebbles” with Stokes numbers of $10^{-2}$ to 1, we postulate that these two observations are not in fact independent. The large particles observed in the coma of Hartley 2 are consistent with this size of pebbles for a range of reasonable disk models given the likely formation location of the comet based on its chemistry. Therefore, while we cannot conclusively state that these indeed are primordial pebbles, it is at least an intriguing possibility that we may be seeing some remnant of these initial pebbles.

If this is true then we expect a trend in constituent pebble size commensurate with their formation location. Therefore, we expect that the majority of comets, which have chemistry consistent with formation in the outer regions of the protoplanetary disk, will have smaller pebbles than those seen in Hartley 2. We note that much smaller pebbles cannot explain the activity of comets if their activity is driven purely by water, however as these comets likely have significant amount of CO this may not prove problematic (Blum et al., 2014, 2015). For example, based on the high D/H ratio (Altwegg et al., 2015) and the N$_2$/CO ratio (Rubin et al., 2015) of comet 67P/ChuryumovGerasimenko, we may expect that it formed in the colder-outer regions of the Solar System and thus would have been likely formed from small, perhaps cm or sub-cm sized pebbles (although we note that the high tensile strength of small particles may require that the pebbles be at least cm in size to explain the observed activity levels (Gundlach et al., 2015)). Indeed, there previous detections of dust in the coma of 67P suggest that the tail and coma is dominated by large 100µm-mm sized particles (Kelley et al., 2008; Bauer et al., 2012; Rotundi,...
et al. (2015) although there were also detections of larger particles, in cm to meter sizes (Rotundi et al., 2015; Sierks et al., 2015). Under the arguments presented in this paper we believe these larger, dusty objects are aggregates, pieces of the cometary crust that have been ejected rather than primordial “pebbles.” Similarly, we expect the “goose bumps” observed on the surface of 67P (Sierks et al., 2015) are not signatures of their component pebbles but instead have been formed by some other mechanism modifying the cometary surface.

5. Acknowledgments

We would like to thank M. Mumma, P. Weissman and M. Kelley for useful discussions. We would also like to thank Jürgen Blum and anonymous referee for their thoughtful suggestions, which have improved this manuscript. This work is supported by the Goddard Center for Astrobiology (a NASA Astrobiology Institute).

References

Adachi, I., Hayashi, C., Nakazawa, K., Dec. 1976. The gas drag effect on the elliptical motion of a solid body in the primordial solar nebula. Progress of Theoretical Physics 56, 1756–1771.

A’Hearn, M. F., et al., Jun. 2011. EPOXI at Comet Hartley 2. Science 332, 1396–.

A’Hearn, M. F., et al., Oct. 2012. Cometary Volatiles and the Origin of Comets. ApJ758, 29.

Altwegg, K., et al., Jan. 2015. 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. Science 347 (27), A387.

Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., Dullemond, C. P., Nov. 2010. Protoplanetary Disk Structures in Ophiuchus. II. Extension to Fainter Sources. ApJ723, 1241–1254.

Bai, X.-N., Stone, J. M., Oct. 2010. Dynamics of Solids in the Midplane of Protoplanetary Disks: Implications for Planetesimal Formation. ApJ722, 1437–1459.

Barge, P., Sommeria, J., Mar. 1995. Did planet formation begin inside persistent gaseous vortices? AAP295, L1–L4.

Bauer, J. M., et al., Oct. 2012. WISE/NEOWISE Preliminary Analysis and Highlights of the 67p/Churyumov-Gerasimenko near Nucleus Environments. ApJ758, 18.
Beer, E. H., Podolak, M., Prialnik, D., Feb. 2006. The contribution of icy grains to the activity of comets. I. Grain lifetime and distribution. Icarus 180, 473–486.

Bitsch, B., Johansen, A., Lambrechts, M., Morbidelli, A., Mar. 2015. The structure of protoplanetary discs around evolving young stars. AAP 575, A28.

Blum, J., Gundlach, B., Mühle, S., Trigo-Rodriguez, J. M., Jun. 2014. Comets formed in solar-nebula instabilities! - An experimental and modeling attempt to relate the activity of comets to their formation process. Icarus 235, 156–169.

Blum, J., Gundlach, B., Mühle, S., Trigo-Rodriguez, J. M., Mar. 2015. Corrigendum to “Comets formed in solar-nebula instabilities! - An experimental and modeling attempt to relate the activity of comets to their formation process” [Icarus 235 (2014) 156-169]. Icarus 248, 135–136.

Blum, J., Wurm, G., Jan. 2000. Experiments on Sticking, Restructuring, and Fragmentation of Preplanetary Dust Aggregates. Icarus 143, 138–146.

Blum, J., Wurm, G., Sep. 2008. The Growth Mechanisms of Macroscopic Bodies in Protoplanetary Disks. ARAA 46, 21–56.

Carrera, D., Johansen, A., Davies, M. B., Jul. 2015. How to form planetesimals from mm-sized chondrules and chondrule aggregates. AAP 579, A43.

Chiang, E., Youdin, A. N., May 2010. Forming Planetesimals in Solar and Extrasolar Nebulae. Annual Review of Earth and Planetary Sciences 38, 493–522.

Chiang, E. I., Joung, M. K., Creech-Eakman, M. J., Qi, C., Kessler, J. E., Blake, G. A., van Dishoeck, E. F., Feb. 2001. Spectral Energy Distributions of Passive T Tauri and Herbig Ae Disks: Grain Mineralogy, Parameter Dependences, and Comparison with Infrared Space Observatory LWS Observations. ApJ 547, 1077–1089.

Cuzzi, J. N., Hogan, R. C., Bottke, W. F., Aug. 2010. Towards initial mass functions for asteroids and Kuiper Belt Objects. Icarus 208, 518–538.

Cuzzi, J. N., Hogan, R. C., Shariff, K., Nov. 2008. Toward Planetesimals: Dense Chondrule Clumps in the Protoplanetary Nebula. ApJ 687, 1432–1447.

D’Alessio, P., Merín, B., Calvet, N., Hartmann, L., Montesinos, B., Apr. 2005. WWW Database of Models of Accretion Disks Irradiated by the Central Star. RMXAA 41, 61–67.
Dello Russo, N., Bonev, B. P., DiSanti, M. A., Mumma, M. J., Gibb, E. L., Magee-Sauer, K., Barber, R. J., Tennyson, J., Mar. 2005. Water Production Rates, Rotational Temperatures, and Spin Temperatures in Comets C/1999 H1 (Lee), C/1999 S4, and C/2001 A2. ApJ621, 537–544.

Delsemme, A. H., Dec. 1998. The deuterium enrichment observed in recent comets is consistent with the cometary origin of seawater. PLANSS47, 125–131.

Fernández, Y. R., Lowry, S. C., Weissman, P. R., Mueller, B. E. A., Samarasinha, N. H., Belton, M. J. S., Meech, K. J., May 2005. New near-aphelion light curves of Comet 2P/Encke. Icarus175, 194–214.

Garrod, R. T., Pauly, T., Jul. 2011. On the Formation of CO$_2$ and Other Interstellar Ices. ApJ735, 15.

Gundlach, B., Blum, J., Keller, H. U., Y. V. Skorov, Y. V., Jun. 2015. What drives the dust activity of comet 67P/Churyumov-Gerasimenko? ArXiv e-prints.

Güttler, C., Blum, J., Zsom, A., Ormel, C. W., Dullemond, C. P., Apr. 2010. The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? I. Mapping the zoo of laboratory collision experiments. A AP513, A56.

Haghighipour, N., Boss, A. P., Dec. 2003. On Gas Drag-Induced Rapid Migration of Solids in a Nonuniform Solar Nebula. ApJ598, 1301–1311.

Harmon, J. K., Nolan, M. C., Ostro, S. J., Campbell, D. B., 2004. Radar studies of comet nuclei and grain comae. pp. 265–279.

Hartogh, P., Lis, D. C., Bockelée-Morvan, D., de Val-Borro, M., Biver, N., Küppers, M., Emprechtinger, M., Bergin, E. A., Crovisier, J., Rengel, M., Moreno, R., Szutowicz, S., Blake, G. A., Oct. 2011. Ocean-like water in the Jupiter-family comet 103P/Hartley 2. Nature478, 218–220.

Hermalyn, B., Farnham, T. L., Collins, S. M., Kelley, M. S., A’Hearn, M. F., Bodewits, D., Carcich, B., Lindler, D. J., Lisse, C., Meech, K., Schultz, P. H., Thomas, P. C., Feb. 2013. The detection, localization, and dynamics of large icy particles surrounding Comet 103P/Hartley 2. Icarus222, 625–633.

Jansson, K., Johansen, A., Oct. 2014. Formation of pebble-pile planetesimals. AAP570, A47.
Johansen, A., Blum, J., Tanaka, H., Ormel, C., Bizzarro, M., Rickman, H., 2014. The Multifaceted Planetesimal Formation Process. Protostars and Planets VI, 547–570.

Johansen, A., Mac Low, M.-M., Lacerda, P., Bizzarro, M., Apr. 2015. Growth of asteroids, planetary embryos and Kuiper belt objects by chondrule accretion. Science Advances 1, no. 3, id 1500109.

Johansen, A., Oishi, J. S., Low, M.-M. M., Klahr, H., Henning, T., Youdin, A., Aug. 2007. Rapid planetesimal formation in turbulent circumstellar disks. Nature 448, 1022–1025.

Kawakita, H., Watanabe, J.-i., Furusho, R., Fuse, T., Capria, M. T., De Sanctis, M. C., Cremonese, G., Feb. 2004. Spin Temperatures of Ammonia and Water Molecules in Comets. ApJ 601, 1152–1158.

Kelley, M. S., Lindler, D. J., Bodewits, D., A’Hearn, M. F., Lisse, C. M., Kolokolova, L., Kissel, J., Hermsyn, B., Feb. 2013. A distribution of large particles in the coma of Comet 103P/Hartley 2. Icarus 222, 634–652.

Kelley, M. S., Reach, W. T., Lien, D. J., Feb. 2008. The dust trail of Comet 67P/Churyumov Gerasimenko. Icarus 193, 572–587.

Kenyon, S. J., Mar. 2002. Planet Formation in the Outer Solar System. PASP 114, 265–283.

Kenyon, S. J., Bromley, B. C., O’Brien, D. P., Davis, D. R., 2008. Formation and Collisonal Evolution of Kuiper Belt Objects. pp. 293–313.

Kretke, K. A., Lin, D. N. C., Oct. 2010. Structure of Magnetorotational Instability Active Protoplanetary Disks. ApJ 721, 1585–1592.

Kretke, K. A., Lin, D. N. C., Garand, P., Turner, N. J., Jan. 2009. Assembling the Building Blocks of Giant Planets around Intermediate-Mass Stars. ApJ 690, 407–415.

Levison, H., Morbidelli, A., Vanlaerhoven, C., Gomes, R., Tsiganis, K., Jul. 2008. Origin of the structure of the Kuiper belt during a dynamical instability in the orbits of Uranus and Neptune. Icarus 196 (1), 258–273.

Lyra, W., Johansen, A., Klahr, H., Piskunov, N., Dec. 2008. Embryos grown in the dead zone. Assembling the first protoplanetary cores in low mass self-gravitating circumstellar disks of gas and solids. AAP 491, L41–L44.
Meech, K. J., Svoren, J., 2004. Using cometary activity to trace the physical and chemical evolution of cometary nuclei. pp. 317–335.

Morbidelli, A., Bottke, W. F., Nesvorný, D., Levison, H. F., Dec. 2009. Asteroids were born big. Icarus204, 558–573.

Mumma, M. J., Weissman, P. R., Stern, S. A., 1993. Comets and the origin of the solar system - Reading the Rosetta Stone. In: Levy, E. H., Lunine, J. I. (Eds.), Protostars and Planets III. pp. 1177–1252.

Nesvorný, D., Youdin, A. N., Richardson, D. C., Sep. 2010. Formation of Kuiper Belt Binaries by Gravitational Collapse. AJ140, 785–793.

Noble, J. A., Dulieu, F., Congiu, E., Fraser, H. J., Jul. 2011. CO₂ Formation in Quiescent Clouds: An Experimental Study of the CO + OH Pathway. ApJ735, 121.

Nolan, M. C., Harmon, J. K., Howell, E. S., Campbell, D. B., Margot, J.-L., Apr. 2006. Detection of large grains in the coma of Comet C/2001 A2 (LINEAR) from Arecibo radar observations. Icarus181, 432–441.

Öberg, K. I., Boogert, A. C. A., Pontoppidan, K. M., van den Broek, S., van Dishoeck, E. F., Bottinelli, S., Blake, G. A., Evans, II, N. J., Oct. 2011. The Spitzer Ice Legacy: Ice Evolution from Cores to Protostars. ApJ740, 109.

Pan, L., Padoan, P., Scalo, J., Kritsuk, A. G., Norman, M. L., Oct. 2011. Turbulent Clustering of Protoplanetary Dust and Planetesimal Formation. ApJ740, 6.

Parker, A. H., Kavelaars, J. J., Petit, J.-M., Jones, L., Gladman, B., Parker, J., Dec. 2011. Characterization of Seven Ultra-wide Trans-Neptunian Binaries. ApJ743, 1.

Pringle, J. E., 1981. Accretion discs in astrophysics. ARAA19, 137–162.

Reach, W. T., Kelley, M. S., Vaubaillon, J., Sep. 2013. Survey of cometary CO₂, CO, and particulate emissions using the Spitzer Space Telescope. Icarus226, 777–797.

Reach, W. T., Sykes, M. V., Lien, D., Davies, J. K., Nov. 2000. The Formation of Encke Meteoroids and Dust Trail. Icarus148, 80–94.

Rotundi, A., et al., 2015. Dust measurements in the coma of comet 67P/Churyumov-Gerasimenko inbound to the Sun. Science 347, 3905.
Rubin, M., et al., 2015. Molecular nitrogen in comet 67p/churyumov-gerasimenko indicates a low formation temperature. Science.

Sierks, H., et al., 2015. On the nucleus structure and activity of comet 67p/churyumov-gerasimenko. Science 347 (6220).

Skorov, Y., Blum, J., Sep. 2012. Dust release and tensile strength of the non-volatile layer of cometary nuclei. Icarus221, 1–11.

Stern, S. A., Sep. 1996. On the Collisional Environment, Accretion Time Scales, and Architecture of the Massive, Primordial Kuiper Belt. AJ112, 1203.

Stern, S. A., Colwell, J. E., Aug. 1997. Accretion in the Edgeworth-Kuiper Belt: Forming 100-1000 KM Radius Bodies at 30 AU and Beyond. AJ114, 841.

Thomas, P. C., et al., Feb. 2013. Shape, density, and geology of the nucleus of Comet 103P/Hartley 2. Icarus222, 550–558.

Trigo-Rodríguez, J. M., García-Hernández, D. A., Sánchez, A., Lacruz, J., Davidsson, B. J. R., Rodríguez, D., Pastor, S., de Los Reyes, J. A., Dec. 2010. Outburst activity in comets - II. A multiband photometric monitoring of comet 29P/Schwassmann-Wachmann 1. MNRAS409, 1682–1690.

Trigo-Rodríguez, J. M., García-Melendo, E., Davidsson, B. J. R., Sánchez, A., Rodríguez, D., Lacruz, J., de Los Reyes, J. A., Pastor, S., Jul. 2008. Outburst activity in comets. I. Continuous monitoring of comet 29P/Schwassmann-Wachmann 1. AAP485, 599–606.

van Dishoeck, E. F., Bergin, E. A., Lis, D. C., Lunine, J. I., 2014. Water: From Clouds to Planets. Protostars and Planets VI, 835–858.

Weidenschilling, S. J., Aug. 2011. Initial sizes of planetesimals and accretion of the asteroids. Icarus214, 671–684.

Whipple, F. L., 1972. On certain aerodynamic processes for asteroids and comets. From Plasma to Planet, 211–+.

Windmark, F., Birnstiel, T., Güttler, C., Blum, J., Dullemond, C. P., Henning, T., Apr. 2012. Planetesimal formation by sweep-up: how the bouncing barrier can be beneficial to growth. AAP540, A73.
Yokochi, R., Marboeuf, U., Quirico, E., Schmitt, B., Apr. 2012. Pressure dependent trace gas trapping in amorphous water ice at 77 K: Implications for determining conditions of comet formation. Icarus218, 760–770.

Youdin, A. N., Goodman, J., Feb. 2005. Streaming Instabilities in Protoplanetary Disks. ApJ620, 459–469.

Zsom, A., Ormel, C. W., Güttler, C., Blum, J., Dullemond, C. P., Apr. 2010. The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? II. Introducing the bouncing barrier. AAP513, A57.