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# Formation of (exo-)planets

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In this small review I will address three recent topics in the field of theoretical planet formation studies. This review is not meant to be complete in any way. It is meant to give an idea where some of the recent developments are.



## 1 Introduction

Thanks to the discoveries of numerous exoplanets and exoplanetary systems around nearby sunlike stars, as well as abundant observational data of protoplanetary disks over the last two decades, the field of planet formation studies has experienced a major boost. However, even some of the most basic questions regarding the formation of planets are not yet answered. The standard scenario for the formation of planets is a gradual growth from submicron sized dust particles all the way to rocky planets, which is sometimes followed up by gas accretion from the protoplanetary disk to form a gas giant planet. Among today's unsolved problems in this process are: How can dust aggregates grow beyond the so-called "meter size barrier"? Do planetesimals acquire sizes $\gtrsim 100$ km by successive merging according to the classic "runaway growth" process, or are they formed big through gravoturbulent formation processes? And how does the gravitational interaction between a planet and its gas disk affect the statistics of exoplanets? These three questions are related to specific phases of the growth process, as shown pictographically in Fig. 1. There are many more unsolved problems in the field of planet formation, but these are the three topics I would like to address in this small review, where it has to be said that my own main research experience lies mostly in the first of the three.

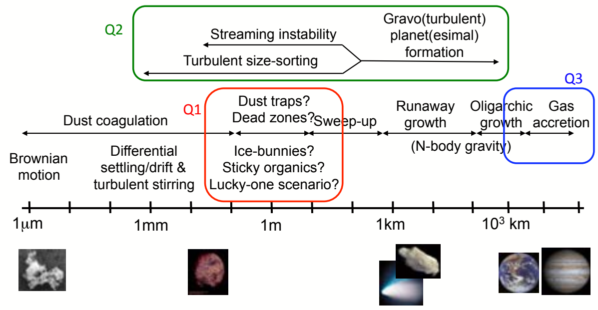


**Fig. 1** The three questions posed in this review are shown here on the size-bar, shown with boxes labelled Q1, Q2 and Q3.

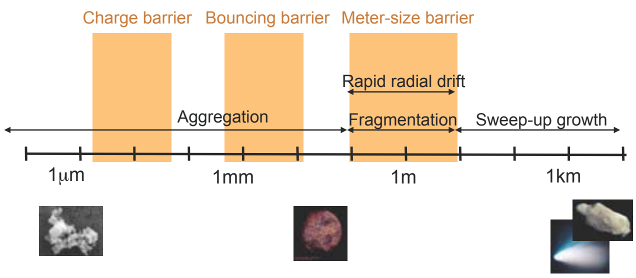


**Fig. 2** The various barriers that dust coagulation has to overcome to grow to planetesimal size. The meter size barrier consists of the fragmentation and the radial drift barrier. See text for details.

## 2 Question 1: how does nature overcome the meter size barrier?

Planet formation starts with the coagulation of dust: a process in which dust particles collide with each other and stick, thus forming aggregates of dust of ever increasing size (see, e.g., Blum & Wurm 2008; Dominik et al. 2007; Güttler et al. 2010). The dust particles that a protoplanetary disk inherits from the interstellar medium are thought to be smaller than about a micron. Such minuscule dust particles are very sticky, and coagulation can proceed without problems – that is, if grain charging does not spoil it (the "charge barrier", Okuzumi 2009, see Fig. 2). As the dust aggregates grow, however, their surface-to-mass ratio declines, and thus the binding between two colliding aggregates becomes less effective. The probability that two aggregates stick when they collide therefore becomes smaller as they grow, leading to the "bouncing barrier" (see Fig. 2) when this probability essentially reduces to zero for equal-size dust aggregates

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(Zsom et al. 2010). If growth proceeds through collisions between unequal size aggregates, or through more sticky materials (e.g. organics, Lodders 2004, or ices Wada et al. 2009), the dust aggregates become larger and the collision velocities increase, because the velocities of larger particles are less damped by gas drag. When such dust aggregates collide at high velocities, they shatter. This is the so-called "fragmentation barrier" (see Fig. 2). While various possibilities exist to overcome the charge- and bouncing barriers, the fragmentation barrier seems a more problematic one, because it essentially resets all the growth that has taken place before. It is a destructive barrier, whereas the other barriers are just suppressing further growth. Since we know that planets, asteroids and comets have formed in our solar system, apparently nature somehow manages to overcome these barriers. However, once the bodies reach several hundreds of meters, gravity starts to become important and will improve the binding force again. The problem is thus really for intermediate sizes, between about a centimeter and hundred meter.

Sticking is, however, not the only problem that nature has to overcome to grow planetesimals from dust. Suppose that we can find ways to form a meter-size body. It will then start to rapidly drift radially inwards toward the star (Adachi et al. 1976; Weidenschilling 1977; Whipple 1972). This is due to the fact that the gas in the disk is rotating with a slightly sub-Keplerian velocity around the star due to the fact that it has a small but non-negligible pressure support. Due to the friction with the gas the dust particles are forced to rotate also at this slightly sub-Kepler velocity. But since they do not feel the compensating pressure support, they feel a net force inward, leading to inward drift. The drift velocity is set by a balance between this inward-pointing force and the velocity-dependent drag force with the gas. This leads to the general result that particles tend to drift in the direction of the gas pressure gradient:

$$\boldsymbol{u}_{\rm dust} - \boldsymbol{u}_{\rm gas} \propto \boldsymbol{\nabla} P_{\rm gas}. \quad (1)$$

Bigger particles have lower surface-to-mass ratio and are therefore less susceptible to gas drag. As a consequence they will reach larger drift velocities. This increase in velocity turns over at about a meter size, whereupon the drift velocity decreases again with size (see Fig. 3). This is called the "radial drift barrier" (see Fig. 2), because it would flush newly formed bodies into the star. Also this barrier is most prominent for particles in the centimeter to hundred meter range. Together, the fragmentation and radial drift barriers are called the "meter size barrier", and it is one of the most serious problems in the theory of planet formation. Taken on its own, the radial drift barrier can be overcome under special circumstances (e.g. Laibe et al. 2012). But the combination with the destructive power of high-speed collisions makes it a major problem. Moreover, the radial drift and fragmentation problems are related because one of the contributions to the high-speed impacts arises from the radial drift velocity itself. This can be seen from Fig. 3.

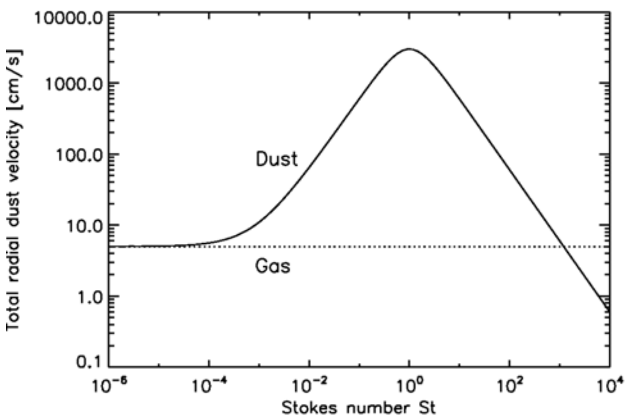


**Fig. 3** Radial drift velocity of dust particles as a function of particle size given in terms of the Stokes number. For particle sizes $\lesssim$1 cm the Stokes number scales linearly with particle size. At 1 AU a body of about 1 meter corresponds to St = 1. Figure taken from Brauer et al. (2008a). A radial velocity of 30 m s$^{-1}$ corresponds to 0.6 AU per 100 years. Moreover, collisions at relative velocities in excess of a few m s$^{-1}$ can lead to fragmentation.

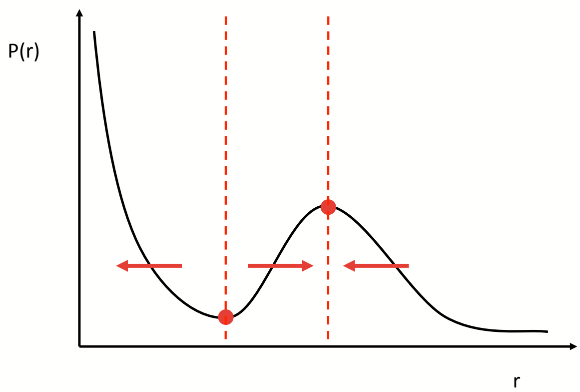


**Fig. 4** Pictographic representation of how a local pressure maximum can trap particles, given that dust drifts in the direction of positive pressure gradient. See text for details.

There are several ideas how nature might solve this problem. One of these ideas is the concept of dust trapping in long-lived pressure bumps. According to Eq. (1) the inward drift occurs due to the fact that we believe that the gas pressure at the midplane of the disk $P(r)$ drops with radius $r$. But what if $P(r)$ is not a monotonically decreasing function of $r$ but has a wiggle, such that there exists an $r_0$ where $\mathrm{d}P/\mathrm{d}r = 0$ and $\mathrm{d}^2P/\mathrm{d}r^2 < 0$ (i.e. a local pressure maximum, see Fig. 4)? Already Whipple (1972) suggested that if this were the case, particles would get trapped there, and the idea was rejuvenated by Garaud (2007) and Kretke & Lin (2007) who argue that the sublimation zones of ices could produce such bumps and by Pinilla et al. (2012) who study the particle trapping in the pressure bump produced by a gap-opening giant planet. Brauer et al. (2008b) showed that it can indeed, under certain conditions, be a region where planetesimals are formed by coagulation.

 

Pressure bumps can also exist much more locally in the form of geostrophic anticyclonic vortices. Such vortices capture dust particles quite efficiently (Barge & Sommeria 1995; Klahr & Henning 1997). Normally a vortex should, by the centrifugal force, expel particles rather than attract them. This is indeed the case with small scale turbulent eddies (e.g. Pan et al. 2011). But if a vortex rotates slowly enough it can be in a so-called "geostrophic balance", which means that its pressure gradients are compensated by Coriolis forces. If the geostrophic vortex rotates in an anticyclonic manner, it has a local pressure maximum at its center, and is held together by inward-pointing coriolis forces. These coriolis forces are responsible for pushing the dust particles toward the eye of the vortex. Meheut et al. (2012b) studied grain trapping in 3-D vortices, and showed that while it is effective, for special grain sizes it leads to vertical convection of the particles instead of concentration at the vortex center.

Such particle-trapping vortices can form through two known mechanisms. If the disk has a negative radial entropy gradient (i.e. the ratio $P/\rho^\gamma$ decreases with radius, where $\rho$ is the gas density and $\gamma$ is the adiabatic index), then the disk could become radially convectively unstable, and produce anticyclonic vortices. This is known as a "baroclinic instability" and was studied in the context of protoplanetary disks by e.g. Klahr & Bodenheimer (2003) and Lesur & Papaloizou (2010). If a disk has strong radial density gradients, the disk can become prone to the "Rossby wave instability", which may also create vortices (Li et al. 2000; Lovelace et al. 1999; Meheut et al. 2012a). Such strong density gradients might occur at the edges of a gap carved out by a massive planet (e.g. Varnière & Tagger 2006) or near dead zone edges (e.g. Lyra et al. 2009).

The centers of these vortices would be ideal locations for the formation of planetesimals. The eye of the vortex, the location where $\boldsymbol{\nabla} P = 0$, is the location where the dust concentrates, potentially leading to huge densities of solids, and thus massively speeding up dust coagulation. Also, if turbulence is weak, this convergence point ensures that particles move slowly with respect to each other. The high velocities shown in Fig. 3 were caused by the background pressure gradient, which is absent in such a convergence point. This means that collisions are gentle, and the fragmentation barrier can thus be avoided. If coagulation indeed produces planetesimals, such dust traps are presumably the locations where this happens.

Current observational technologies do not yet have the angular resolution to directly detect such vortices in the $\sim$1 AU planet forming regions of protoplanetary disks. However, recent observations with SMA and ALMA are showing evidence for huge banana-shaped structures in the outer regions of disks (Brown et al. 2009; Casassus et al. 2013), which are consistent with being elongated anticyclonic vortices (Regály et al. 2012), presumably with dust trapping occurring inside (Birnstiel et al. 2013). At those large distances from the star, it is not the meter-size bodies that experience the destructive velocities, but millimeter particles. Coincidentally, and luckily, these are precisely the grain sizes for which (sub-)millimeter telescopes are most sensitive. By studying how Nature deals with the millimeter-size barrier at $\sim 50$ AU we can hopefully, and by proxy, learn about how Nature overcomes the meter-size barrier at 1 AU. And with ALMA still increasing its power, we can thus expect further spectacular discoveries in the near future.

However, the efficient trapping of particles does not yet answer the question *if* coagulation will indeed be efficient. If turbulence is too weak, collisions might happen too rarely to cause much coagulation. And even at very low collision velocities, the bouncing barrier might still play a role. If, on the other hand, turbulence is too strong, the fragmentation barrier is back.

One way to overcome the fragmentation barrier in spite of strong turbulence is the sweep-up scenario proposed by Windmark et al. (2012a). In this scenario most particles are stuck at millimeter sizes by the bouncing barrier. They form a sea of pebbles. If, for some reason, a few pebbles still manage to grow beyond this barrier (it can be an absurdly small fraction), they can continue to grow by sweeping up the other pebbles. This will be easier because unequal size collisions can more easily dissipate energy and thus more easily lead to sticking. These "lucky guys" avoid the fragmentation barrier because they are so rare that they never meet each other (they only meet pebbles). At the beginning they represent only a minute fraction of the total mass of solids, but as they grow, this fraction increases. Windmark et al. (2012b) and Garaud et al. (2013) (see also earlier work by Okuzumi et al. 2011) show that a possible key to the lucky ones is the fact that particles of given properties do not collide always with the same velocity, but follow instead a velocity distribution function.

Another idea is that maybe we systematically underestimate the stickiness of dust particles. The presumed weakness of dust aggregates originates primarily from laboratory experiments with quartz spherules (Blum & Wurm 2008). On the other hand, according to Wada et al. (2009), icy dust particles are so sticky that dust aggregates can survive collisions of up to 10 or even 50 m s$^{-1}$. This can lead to efficient and very fractal growth (Okuzumi et al. 2012). It is not easy to verify if these authors are right, because laboratory experiments with icy dust particles are not yet available. If they are right, however, then it would immediately eliminate the fragmentation barrier in regions beyond the snow line in the disk. The problem remains, however, for the Earth-forming region.

## 3 Question 2: are planetesimals formed small or big?

So far we have assumed that planetesimals are formed by the gradual coagulation of ever larger dust aggregates. However, this notion has been challenged over the last decade.

 

There have been several mechanisms proposed that may "skip" a large portion of this gradual growth phase by jumping from millimeter or decimenter sized pebbles or rocks straight to many-kilometer size gravitationally bound planetesimals. This idea is not new. Already Goldreich & Ward (1973), based on earlier work by Safronov, introduced the idea that as dust particles grow and settle toward the midplane of the disk, they form an ever denser midplane layer of solids. If the disk is virtually non-turbulent (i.e. laminar) there is no force that could stir the particles up, and the layer can only become denser with time, until it becomes so geometrically thin that it becomes gravitationally unstable. When this happens, the layer fragments into gravitationally bound clouds of pebbles which contract to form planetesimals. This is often called the Safronov-Goldreich-Ward (SGW) instability. While this scenario sounds extremely appealing, it was shown to have some problems. Weidenschilling (1980) and Cuzzi (1993) showed that this dense layer of solids would become turbulent well before it becomes thin enough to gravitationally fragment. The reason is simple: the gas, with $\mathrm{d}P/\mathrm{d}r < 0$, moves at a slightly sub-Kepler rotational velocity. When the dust layer becomes so geometrically thin that it becomes denser than the gas, it no longer feels the support by the gas pressure and begins to move at a Kepler speed. This leads to a shear between the dust layer and the gas above and below. This shear leads to Kelvin-Helmholtz instability and hence to turbulence. This would inhibit this process. Note that this would not be the case at the centers of anticyclonic vortices, which would make them (if they exist) also potential regions where the SGW instability might operate. But for a long time the SGW instability was considered a dead end, though some potentially working scenarios were nevertheless identified (Weidenschilling 1997; Youdin & Shu 2002).

A much different avenue of "jumping over the meter-size barrier" was proposed in a sequence of papers by Cuzzi and Hogan (incl. Cuzzi et al. 2001, 2008; Hogan & Cuzzi 2007). This picture is based on the known phenomenon of spontaneous particle clustering in turbulent flows (e.g. Squires & Eaton 1990). We know this phenomenon from everyday life, e.g. when fallen leafs in the autumn get clustered due to turbulent winds. The same will happen to dust particles in the turbulent protoplanetary disk. Particles get expelled from regions of large vorticity (due to the centrifugal force; of course, unless the vortex is in geostrophic balance, see Sect. 2) and get concentrated in regions of large strain (simply put: the corner-points between eddies). Rarely do these clusterings lead to very strong dust density enhancements, but the chance that such extreme clustering happens is non-zero nevertheless. If such a rare event happens, it seldom involves a large amount of dust, but also this chance is not zero. Considering the huge number of turbulent eddies in a protoplanetary disk at every given time, and the huge amount of time available (millions of orbits), even small chances per turbulent eddy per orbit will add up to considerable chances in total.

In the above mentioned papers, and in subsequent work by Chambers (2010), a model is presented that attempts to estimate the rate at which, by sheer chance, a sufficient amount of dust (in the form of mm-size pebbles) is concentrated sufficiently much that it will subsequently be held together by gravity, upon which, by slowly expelling the remaining gas, it will form a large ($\sim$100 km size) planetesimal. While this model is highly appealing, it should be understood that it is based on scaling relations to extrapolate results from numerical simulations, which inherently have limited spatial resolution, to the real world, where turbulence eddies span many orders of magnitude in size. As pointed out by Pan et al. (2011) these scaling relations might be too optimistic in the above papers, meaning that in reality the probabilities of spontaneous planetesimal formation might be prohibitively low. It is clear, however, that the last word is not said on this topic, and it remains an exciting possibility.

Closely linked, but focused on the larger turbulent eddies and larger initial dusty bodies, is the scenario described by Johansen et al. (2007). In this scenario the particles must first grow to sizes of about a decimeter or so, upon which they start to be *partially* decoupled from the gas. Like in Cuzzi's mechanism this leads to clumping, but because the bodies are much larger than in Cuzzi's case, they couple to much larger eddies. This means that concentrations with sufficient mass to remain gravitationally bound are reached within a few orbital time scales. Compared to Cuzzi's mechanism, where we have to wait until chance produces unusually large concentrations, in Johansen's mechanism the typical concentrations are already large enough for direct gravitational collapse. Because this all takes place at large scales, Johansen's models also include the Coriolis forces and orbital shear, which Cuzzi's models do not. Johansen et al. (2009) found that magnetorotational turbulence yields, in addition to a Kolmogorov-type turbulent cascade to ever smaller scales, also an inverse cascade to ever larger scales, leading to the formation of so-called "zonal flows". These zonal flows are very similar to stretched anticyclonic vortices or pressure ridges, the ones described in Sect. 2, and can thus contribute to the efficiency of planet formation, but their survival time appears to be limited to perhaps a 50 orbits or so (Dittrich et al. 2013).

Even if a disk is non-turbulent to start with, there are several mechanisms by which the dust-gas bidirectional coupling could spontaneously lead to turbulence. I already alluded to this in the beginning of this section, where such spontaneous turbulence was used as an argument against the SGW instability. It turns out, however, that this driving of turbulence could also be beneficial to particle clustering. Youdin & Goodman (2005) showed that the co-existence of large quantities of dust and gas can be prone to the "streaming instability". This is a kind of traffic-jam instability by which dense dust concentrations move at different speed than the rest of the dust particles, and thus tend to collect the latter. As shown in the non-linear models by Johansen

& Youdin (2007) this instability leads to very clumpy distributions of dust which may possibly trigger planetesimal formation in the same way as described above. I will therefore combine them by calling this the Johansen & Youdin gravoturbulent planetesimal formation scenario.

Both scenarios (the Cuzzi & Hogan and the Johansen & Youdin scenarios) may be related, and it is very well possible that the Cuzzi & Hogan clustering could kick-start the Johansen & Youdin gravoturbulent planetesimals formation scenario. Both scenarios seem to lead to pretty large planetesimals, of the order of hundreds of kilometers. This appears to be because you need to bring a sufficiently large amount of material together to be sufficiently gravitationally bound to avoid being ruptured apart again by hydrodynamic forces. If this is true, then planetesimals would form big. Morbidelli et al. (2009) argue that the size distribution of the present day asteroid belt indeed provides a strong indication that this was the case, although Weidenschilling (2011) has subsequently disputed this. Also here it seems that the last word has not yet been spoken.

## 4 Question 3: how does planet-disk interaction affect planet formation?

The third and final topic I would like to address is the question what happens if, by agglomeration of planetesimals, a planetary embryo forms that will be massive enough to start gravitationally interacting with the gaseous disk. As a result, it will start attracting a hydrostatic pseudo-atmosphere from the gas disk (e.g. Inaba & Ikoma 2003). Eventually the protoplanet will also start migrating and thus leave the region where it was born. As it does so, it will enter regions where fresh reservoirs of planetesimals still exist, and it can thus continue to grow beyond what would otherwise be the isolation mass (Alibert et al. 2005). At some point, when the mass of the rocky planet has reached about 10 Earth masses, the pseudo-atmosphere can no longer hydrostatically sustain itself, and will start to collapse. This means that new gas can be dumped onto the planet without hydrostatic obstruction, and a runaway gas accretion occurs (Pollack et al. 1996), leading to the formation of a gas giant planet. This model makes an interesting prediction, as was shown by Mordasini et al. (2009), their Fig. 3, that in the statistics of the number of existing exoplanets as a function of exoplanet mass there should be a peak of ice giants (around 10 Earth masses), because any planets exceeding this mass will "quantum leap" to gas giant masses and thus leave a dearth of planets around 40 Earth masses, and planets well below 10 Earth masses do not migrate sufficiently (according to their model) to sweep up fresh planetesimals and grow beyond the isolation mass. It is interesting to note that the dip around 40 Earth masses appears to be confirmed in observational data from HARPS (Mayor et al. 2011), which lends credence to the picture of runaway gas accretion as the way to form gas giant planets, at least those that are close enough to the host star to be picked up by radial velocity surveys.

The issue of planetary migration is, however, far from understood. This is an immensely complex topic, and it would be impossible to do justice to this topic in a short review such as the present one. So I will focus more on the effect of migration on planet formation than on the mechanisms planetary migration itself (for that, see, e.g., the review by Kley & Nelson 2012). And let me limit myself even more by focusing on the recent development of migration convergence. It was found by Masset et al. (2006) that if a strong local density maximum exists in the disk, it could act as a type I planet migration trap. Morbidelli et al. (2008) subsequently showed that such a migration trap could lead to collecting numerous planetary embryos which, through their forced proximity, will have a high chance of merging and thus forming the core of a gas giant planet. It is interesting to realize that a massive pressure bump thus appears to be trapping *both* dust particles (through gas drag) *and* planets (through gravitational torques). If a huge dust trap leads to the formation of copious amounts of planetary embryos (Lyra et al. 2009), they might stay close to their birthplace because the migration convergence zone is going to be nearby. The question is then how this will develop. Sándor et al. (2011) studied this using an N-body approach where the migration-inducing gravitational torques were implemented using the fitting formulae by Paardekooper et al. (2010, 2011). They found that the planets tend to arrange themselves in closely packed circular orbits. Furthermore, they found that whenever a new embryo is injected, the system has to re-adjust, possibly leading to mergers and the formation of, eventually, a large 10 Earth mass core.

However, it is not yet 100% clear whether large pressure bumps in a disk will indeed trap planets, in spite of current indications that they will. Numerical hydrodynamic modeling of migration of very low mass planets is challenging because it requires extreme numerical spatial resolution to resolve the co-orbital region, as well as the treatment of the sub-Kepler rotation of the gas (see the gas flow patterns around low mass planets computed by Ormel 2013). It is also not clear whether the easy-to-use formulae of Paardekooper can be used under the extreme circumstances found there (extreme density gradients, and multiple closely packed planets). More research is evidently needed.

Migration traps can also be caused by much more subtle effects. As has been shown by Paardekooper & Mellema (2006) and Baruteau & Masset (2008), radiative effects can strongly affect the migration rate of a planet and, as shown by, e.g., Kley & Crida (2008), even cause outward migration. This will also lead to migration converging points, which will change position as the disk evolves (Lyra et al. 2010). The precise location of these convergence points will, however, depend very much on how well we will be able to treat the radiation transfer and radiation-hydrodynamics inside the disk (see e.g. Bitsch et al. 2013). This is a problem of well-known difficulty, but not so well-known solutions, leaving plenty of interesting areas of investigation open.

 

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