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ALMA Observations of the Epoch of Planet Formation

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Planetary systems form in the discs of gas and dust that orbit young stars. In the past few years, observations of these discs at (sub-)millimetre wavelengths with very fine angular resolution have started to uncover the hallmarks of small-scale substructures in the spatial distributions of their pebble-sized particles. These are some of the fundamental signatures of the planet formation epoch, since they trace localised concentrations of material that facilitate the formation of much larger planetary building blocks, and may themselves be created by young planets interacting with their birth environments.

Circumstellar discs and planet formation

The effort to understand our origins, and therefore to add some existential context to our place in the universe, is a fundamental component of astrophysics research. This more philosophical aspect of the field takes on a starkly practical tone for the specialised topic of planets. In less than three decades, the planetary science landscape has been completely transformed, going from the modest membership of our lonely Solar System to a galaxy that is literally teeming with exoplanets. Astronomical observations of this abundance of other worlds have guided theoretical studies that aim to explain the key physical properties of the exoplanet population. One crucial outcome of all that work is the realisation that many of the most basic planetary characteristics (masses, orbits, atmospheric compositions, etc.) are imprinted around the time a planet is formed. This implies that key aspects of planetary systems hinge on complex interactions with their birth environment — specifically, remnant material in the discs that orbit young stars.

The origins of the Solar System have long been associated with a progenitor disc structure, thanks to the recognition that the planets orbit the Sun in the same direction and confined to the relatively narrow ecliptic plane. But the connection between stars and discs is both more general and more fundamental. Circumstellar discs are the natural consequences of angular momentum conservation during the star formation process. They are created when a rotating overdensity in a molecular cloud collapses under its own gravity, which channels material into a rotationally-supported flattened morphology that both feeds mass onto the central star and, roughly a million years later, transforms into a planetary system.

It is not an exaggeration to claim that the relatively brief life of a disc both shapes and fundamentally links the properties of a star and its associated planets. In that sense, measurements of the properties of these discs are invaluable because they provide unique insights that help us build a more robust theory of star and planet formation. Over just the past few years, the disc community has focused intently on several interrelated issues that lie at the heart of the planet formation process. Below we highlight these studies in the context of a new, expansive survey of discs at very high angular resolution with the Atacama Large Millimeter/submillimeter Array (ALMA). First, we emphasise why the evolution of solids in discs is so fundamental for planet formation. Next, we explain how that evolution (and the key observables) is thought to be controlled largely by interactions with fine-scale structures in the gas disc. Then we discuss what new observations are revealing about these issues in the contexts of both disc evolution and planet formation.

The evolution of disc solids

That disc solids are important for planet formation might seem obvious. Most of the known exoplanets are small and presumed to be rocky, and even the gas giants in our Solar System are known to have massive solid cores. But making this connection requires faith in a growth process on remarkable scales; in only a few million years, the sub-micron-sized dust grains that are incorporated into a disc when it forms must increase by at least 10 orders of magnitude in size (roughly 30 orders of magnitude in mass) through a sequence of collisional agglomerations, to become a population of km-scale “planetesimal” building blocks. At that point, gravity aids their subsequent evolution to terrestrial planets or giant planet cores. In the standard theory, making planetesimals is the biggest hurdle in the planet formation process. In fact, the problems start early, with growth bottlenecks at “pebble” (mm/cm) size scales.

All of the standard planet formation models assume that the gas disc is smooth, such that its pressure decreases monotonically with distance from the host star. The corresponding radial pressure gradient imposes a small outward force on a parcel of gas, slowing its orbital speed below the Keplerian velocity. That velocity difference between the gas and the solids embedded in it is small, on the order of 1%, but it has dramatic implications for their mutual interactions. At a given location (set of physical conditions), solid particles with a specific range of sizes start to decouple from the gas flow. Those particles then feel the sub-Keplerian velocity of the gas as an aerodynamic drag force that saps their angular momentum and sends them spiralling inwards towards the global pressure maximum in the inner disc (Weidenschilling, 1977).

This migration of solids, termed radial drift, introduces two important problems. First, it enhances the relative velocities between particles, leading to destructive collisions (fragmentation). Second, and more important, because the drift timescale is much shorter than the typical collision (growth) timescale, the corresponding depletion of drifting particles effectively limits further growth (for example, Takeuchi & Lin, 2002). In the big picture, this depletion of the solids implies that planetesimal formation is inhibited beyond roughly 10 astronomical units (au). At larger radii, representing the bulk of the disc mass, radial drift is most efficient for pebbles (which achieve migration speeds on the order of 1 au per orbital period). The result is a pronounced radial size segregation of the solids; larger particles are preferentially located closer to the star. The typical disc should have its mm/cm-sized pebbles concentrated in the inner disc (for example, Birnstiel & Andrews, 2014).

In a sense it is fortunate that this migration process is so significant for pebbles, since these are the last particles in the growth sequence that are directly observable through their thermal continuum emission. Such emission is most efficient at a wavelength comparable to the particle size, making the (sub-)mm part of the spectrum the optimal tracer, and therefore ALMA the premier facility for studying this evolutionary process. Measurements of the spatial distribution of the mm "colour" (spectrum shape) provide qualitative support for the radial size segregation predicted by the standard theory for the evolution of disc solids (for example, Pérez et al., 2012). But the extended morphologies of the mm-wavelength continuum emission from many nearby discs are in clear, quantitative conflict with these predictions (for example, Tripathi et al., 2017).

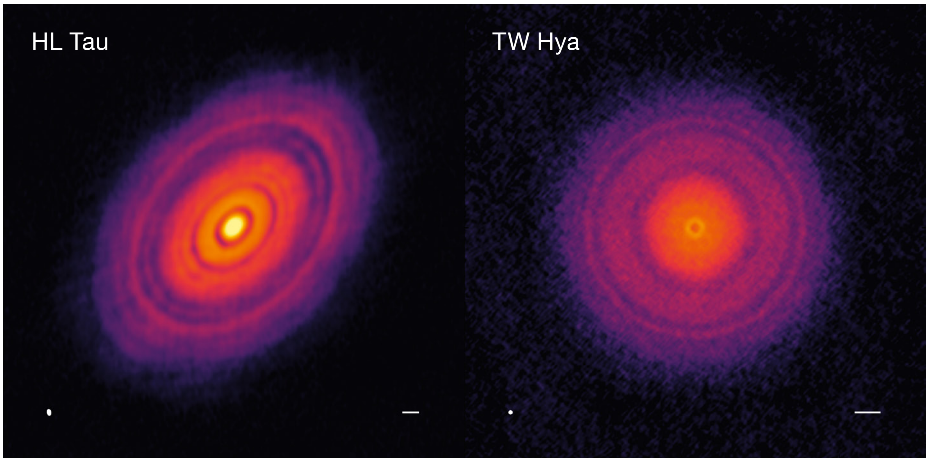

Figure 1. ALMA images of the 1-mm continuum emission from the HL Tau (ALMA Partnership et al., 2015) and TW Hya (Andrews et al., 2016) protoplanetary discs. With access to high angular resolution, a series of concentric bright rings and dark gaps on scales of a few astronomical units (au) become apparent. The scale bars mark 10 au; the synthesised beam (resolution element) is shown as an ellipse in the lower left corner of each image.

In short, resolved observations of mm-continuum emission from discs do indicate that the growth and migration of disc solids are occurring, but they also point to substantial tension with the predicted efficiency of those processes. The observed migration is less pronounced than would be expected for standard assumptions.

A solution in substructures

The most natural way to reconcile this discrepancy is to relax the standard assumptions; gas discs are probably highly structured, not smooth. At any local pressure maximum, there is no force contribution on a parcel of gas from a pressure gradient (by definition), so it will orbit at the Keplerian velocity. This eliminates the drag force on the solids, substantially prolonging the drift timescale. In effect, a local gas pressure maximum is a particle "trap"; solids will migrate toward it and then park there. In addition to solving the drift timescale problem, the associated concentration of solids (relative to gas) could trigger rapid planetesimal formation via the gravitational and/or streaming instability.

The first and clearest evidence for such particle traps came from mm continuum observations of "transition" discs, which appear as emission rings that peak tens of au from their host stars (Andrews et al., 2011; Pinilla et al., 2018). But this subset of the general disc population is rare (about 10%); it is unlikely to represent the general solution to the efficiency issues noted above. Nevertheless, the mechanism is sound; the issue is perhaps related to scales. The leading hypothesis is that the "normal" disc population is riddled with smaller gas pressure modulations with lower amplitudes — substructures — that perform the same roles in concentrating solids (Pinilla et al., 2012).

The commissioning of the highest angular resolution mode available with the ALMA interferometer brought stunning confirmation of this hypothesis. Images of the mm continuum emission from the HL Tau and TW Hya discs at roughly 30 milliarcsecond resolution, reproduced in Figure 1, revealed a series of narrow (a few au wide) ring and gap substructures (ALMA Partnership et al., 2015; Andrews et al., 2016). Evidence for similar features at coarser resolutions has also continued to percolate out from serendipitous ALMA discoveries, and is complemented by analogous features in infrared images of starlight scattered off much smaller dust grains (thereby tracing the gas) in the disc surface layers (for example, Avenhaus et al., 2018).

In a few short years, these measurements have fundamentally shifted assumptions about disc properties in a new generation of planet formation models. Much of the current focus in the field is on the origins of the observed substructures, which range from migration modulations near volatile condensation fronts, to the complex dynamical interplay between magnetic fields, gas and solids, to the gravitational interactions between disc material and very young planets. At first glance, the last option seems like a circular logic; substructures are essential to make planetesimals (and therefore planets), but then we are invoking planets as the origins of substructures. But this is not necessarily a problem; it merely implies that planetesimal (and thereby planet) formation occurs efficiently, in the earliest stages of disc evolution. If this is true, the substructures we observe are probably a second generation of features, and the underlying framework of planet formation models will see a drastic modification.

In any case, the natural next step is to learn more about the demographics of small-scale disc substructures, and to use that information to help understand their origins.

The Disc Substructures at High Angular Resolution Project (DSHARP)

To that end, our team has conducted one of the preliminary ALMA Large Programs to measure the 1.25-mm continuum emission (and CO J = 2–1 emission line) for 20 nearby discs at an angular resolution of 35 milliarcseconds, equivalent to around 5 au in projected spatial resolution (Andrews et al., 2018). The goals of the Disc Substructures at High Angular Resolution Project (DSHARP) are to assess the prevalence, forms, sizes, spacings, symmetry, and amplitudes of substructures, to get a preliminary look at how they might depend on the bulk disc or stellar host properties, to compare those characteristics with hypotheses for their origins, and to facilitate a community-wide effort to build on those results. This last aspect is achieved with the full DSHARP data release, including calibrated visibilities, images, scripts, and various secondary products[1].

The ALMA continuum images reveal that all discs in the DSHARP sample contain substructures indicative of localised pebble concentrations. These features are located over a wide range of disc radii (from 5 to 150 au) and exhibit a diversity of characteristic size scales (a few au to tens of au) and intensity contrasts (a few percent to roughly a factor of two). Concentric bright rings and dark gaps in the emission distribution are by far the most common forms of substructure, as illustrated in Figure 2 (Huang et al., 2018a). While simple in form, these rings and gaps have a diverse range of locations (and spacings), widths, and amplitudes; moreover, there is no clear association between their properties and any characteristics of the stellar hosts. These substructures appear to be circular (after accounting for the disc viewing angles) and azimuthally symmetric. Only two cases show obvious deviations from axisymmetry, in the form of narrow, arc-like features (Isella et al., 2018; Pérez et al., 2018). Some of the continuum morphologies can be decomposed solely into narrow rings, and occasionally additional gaps are even present in the CO line emission well beyond the radii where continuum emission is detected (Guzmán et al., 2018).

The sizes, amplitudes, and locations of many of the bright ring features are found to be consistent with theoretical predictions for particle trapping at local gas pressure maxima, with densities that are nominally high enough to facilitate rapid planetesimal formation (Dullemond et al., 2018). Alongside the fact that there is no connection between the locations or spacings of these features with the stellar host luminosities (and thereby their temperatures), there is no support for the hypothesis that volatile condensation fronts are associated with substructures in the DSHARP sample discs (Huang et al., 2018a). While some viable, though not yet quantitatively predictive, alterna-

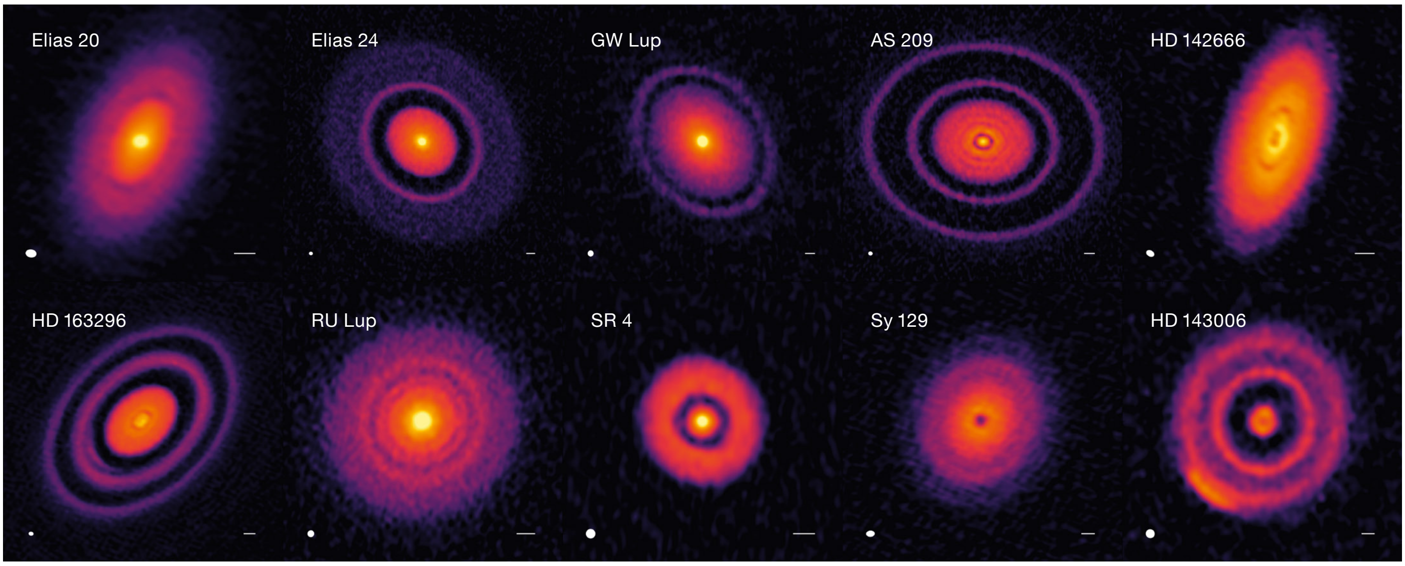

Figure 2. A DSHARP image gallery of the 1.25-mm continuum emission from a subset of the discs that exhibit a diverse set of ring and gap substructures (Andrews et al., 2018; Huang et al., 2018a; Guzmán et al., 2018; Isella et al., 2018; Pérez et al., 2018).

tive mechanisms for producing these kinds of substructures exist, there are compelling signals that they may be produced by planet-disc interactions. Some of the substructures appear to have resonant spacings and double-gap morphologies similar to predictions from hydrodynamics simulations; the arc features noted in two cases are qualitatively similar to models of vortex trapping near giant planet perturbers, and a new suite of hydrodynamics simulations provides compelling comparisons to many of the observed continuum emission morphologies (Zhang et al., 2018). For some reasonable assumptions, those simulations suggest that the observed disc gaps are plausibly opened by planets with masses 10 to 100 times as large as the mass of the Earth and semimajor axes from roughly 10 to 100 au.

The five discs in the DSHARP sample that are not shown in Figure 2 are dominated by a different substructure morphology: a pronounced spiral pattern. The two of these shown in Figure 3 are known triple star systems (Kurtovic et al., 2018); the discs around the primaries show the clear spiral perturbations that are theoretically expected from tidal interactions in such systems. The CO data in both cases are particularly interesting, revealing clear evidence for misalignments between the disc and orbital planes as well as tidal stripping from previous encounters. The remaining three discs with spiral substructures orbit single stars; their spectacular continuum maps are shown in Figure 4 (Huang et al., 2018b). Each of these discs has a symmetric two-armed morphology that spans the full extent of the continuum emission. These patterns are strikingly complicated; they appear to bifurcate or merge into concentric rings, and in each case at least one circular gap is superposed on the spiral. In these systems, it seems likely that multiple mechanisms are responsible for generating the observed features. But in terms of the spiral component, it is interesting to note that these tend to be the largest, coldest discs in the DSHARP sample. That lends at least some anecdotal support to the idea that a global gravitational instability may be operating.

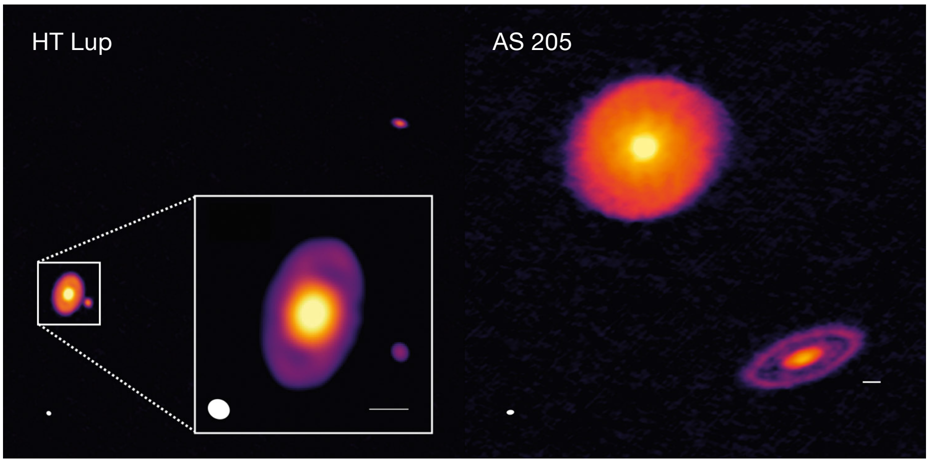

Figure 3. Images of the 1.25-mm continuum emission from discs in the two triple systems in the DSHARP sample (Kurtovic et al., 2018). Note the two-armed spiral morphologies of the discs around the primary stars, indicative of dynamical interactions between the individual components.

Closing thoughts: the start of observational planet formation studies

The DSHARP dataset and preliminary results, along with the many related studies that they build upon, herald the start of a new era in planet formation research. Where much of the effort had previously been theoretical in nature, ALMA and cutting-edge adaptive optics facilities in the infrared promise to drive rapid advances on the observational side. There are many different avenues to pursue that can better place the DSHARP results in context, including extending the sample in orthogonal directions (for example, younger discs, fainter or smaller discs), folding in complementary datasets

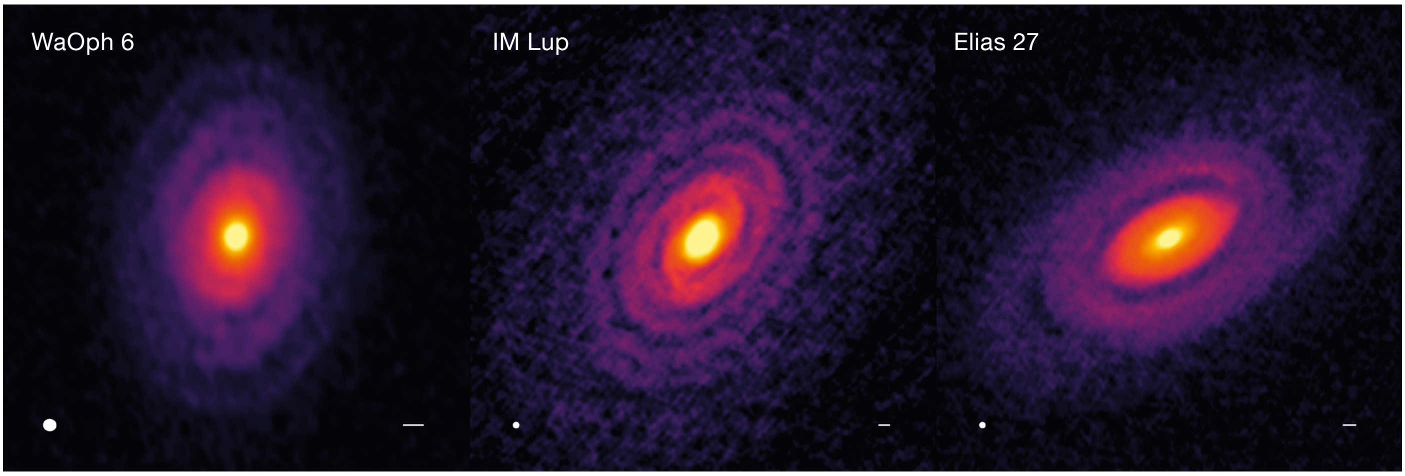

Figure 4. The striking spiral morphologies in the 1.25-mm continuum emission from a small subset of the DSHARP sample discs, in this case for single (isolated) hosts (Huang et al., 2018b). The spiral patterns are complex and superposed with circular features.

(continuum measurements at a longer wavelength to explore the particle trap properties, molecular spectral line or scattered light images to look for related gas signatures, etc.), and undertaking more detailed modelling of individual targets to directly confront theoretical predictions. In any case, ALMA is proving to be a transformational tool. The early results using ALMA data described here should serve as launching points that mark a productive shift in the field, where new data and analyses push towards a new model that robustly connects the growth and migration of disc solids to the planet formation process, and thereby the exoplanet population we observe around nearby main-sequence stars.

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Links

[1] Data Release webpage for DSHARP: https://almascience.org/alma-data/lp/DSHARP

D. Kordan/ESO

ALMA antennas are located at the Chajnantor Plateau at an altitude of 5000 metres, one of the driest places in the world.