Exploring the Formation and Evolution of Planetary Systems
Proceedings IAU Symposium No. 299, 2013
M. Booth, B. C. Matthews & J. R. Graham, eds.

doi:10.1017/S1743921313007977

Radio Interferometry Observations of the Hallmarks of Planet Formation

Sean M. Andrews[1]

[1]Harvard-Smithsonian Center for Astrophysics
60 Garden Street, Cambridge, Massachusetts 02138, USA
email: sandrews@cfa.harvard.edu

Abstract. Some of the fundamental processes involved in the evolution of circumstellar disks and the assembly of planetary systems are just now becoming accessible to astronomical observations. The new promise of observational work in the field of planet formation makes for a very dynamic research scenario, which is certain to be amplified in the coming years as the revolutionary Atacama Large Millimeter/submillimeter Array (ALMA) facility ramps up to full operations. To highlight the new directions being explored in these fields, this brief review will describe how high angular resolution measurements at millimeter/radio wavelengths are being used to study several crucial aspects of the formation and early evolution of planetary systems, including: the gas and dust structures of protoplanetary disks, the growth and migration of disk solids, and the interactions between a young planetary system and its natal, gas-rich disk.

Keywords. circumstellar matter, planetary systems: formation, planetary systems: protoplanetary disks, radio continuum: stars, radio lines: stars, submillimeter

1. Introduction

Planet formation occurs in the dusty, gas-rich disks that orbit young stars. But, although astronomical observations have been probing these disks for nearly thirty years, it is only relatively recently that the quality and diversity of the available data have become sufficient to facilitate quantitative insights on the planet formation process. In that sense, this is a particularly exciting time for the field: the *direct* study of the formation and early evolution of planetary systems is poised to move from a primarily theoretical topic to one that is richly informed and empirically constrained by a deluge of new observational input. Fundamental to these high expectations is the revolutionary enhancement in sensitivity and resolution to circumstellar disk material that will be provided by the new ALMA interferometer, operating at wavelengths from ∼0.35–3.5 mm.

The excitement surrounding the ALMA project in the disk community is due to the long-awaited high spatial and spectral resolution access to some of the most fundamental tracers of disk material. The wavelength range from 350 μm to ∼1 cm (herefafter termed “radio” for convenience) is incredibly rich in physical diagnostics of disk material, primarily because the vast majority of the disk volume is literally quite cool (∼10-100 K). Longward of ∼500 μm, the thermal continuum emission radiated by dust grains is relatively bright (>1000× the stellar photosphere; so no contrast issues) and optically thin (Beckwith *et al.* 1990). Therefore, the continuum surface brightness profile is a good proxy for the radial structure of the dust disk: $I_\nu \propto \kappa_\nu \Sigma_d T_d$, where κ_ν are the dust mass opacities, Σ_d the surface densities, and T_d the (midplane) temperatures (Andrews *et al.* 2009; Isella *et al.* 2009). Moreover, the radio spectrum is richly populated with the pure rotational transitions of simple molecules, providing a wealth of spectral line data that inform our understanding of gas disk structures, chemistry, and kinematics.

Despite the remarkable physical diagnostic capabilities of disk tracers in the radio, the volume of data on the subject has so far been small due to the limited capabilities of current interferometers. As of this writing, the continuum emission from ∼50 disks has been imaged at sub-arcsecond resolution; a sparse subsample of only ∼10 of those disks have been probed in molecular line emission on similar scales (and those usually only in the most abundant tracer, CO, and its primary isotopologues). To give some perspective on future expectations, I would estimate that with the enhanced capabilities of ALMA we will eventually see these numbers grow into the thousands. In essence, the fundamental promise of ALMA in the field of planet formation is really its ability to deliver on the key demographic properties of circumstellar disks. But what is it we want to learn?

In this brief review, I will quickly highlight three issues that are at the forefront of the field (and driving intense interest with ALMA in its early science mode), based on the current state-of-the-art radio interferometry observations of protoplanetary disks: (1) the signposts of young planetary systems and disk-planet interactions; (2) the growth and migration of disk solids; and (3) prospects for quantifying the gas reservoirs in disks.

2. Transition Disks: Evidence for Young Planets?

Theoretical models of the planet formation process tend to impose disk properties (sometimes informed by observational constraints) as initial conditions, and then run a complex set of physical and/or statistical simulations in an effort to reproduce some of the key demographic features of the exoplanet population (e.g., Ida & Lin 2004, 2005; Alibert *et al.* 2005; Mordasini *et al.* 2009). The implicit assumption in these models is that the physics involved in the formation and early evolution of a planetary system is understood well enough to be effectively parametric and deterministic. In a statistical sense, that assumption might be valid: but the behavior of a young planetary system in its early stages, while still embedded in its natal disk reservoir, can be quite complex (see the review by Kley & Nelson 2012). Once a planet has formed, strong feedback between it and the surrounding disk material will modify the planet mass and orbit on a relatively short timescale (e.g., Papaloizou *et al.* 2007; Baruteau & Masset 2012). Indeed, these early evolutionary effects imply that the demographic features in the exoplanet population do not truly reflect the system properties at the formation epoch: therefore, in a sense it is these planet-disk interactions that are the "initial conditions" worth worrying about. Ideally, we want to place more concrete, empirical constraints on these interactions to facilitate improvements in the planet formation models. A direct search for young planets is difficult (although see the contribution by Ireland & Kraus in these proceedings), but an indirect approach aimed at interpreting the signatures of planet-disk interactions manifested in perturbations to the remnant disk structure is more promising.

A planet that forms in a disk will open a narrow gap around its orbital radius, a_p, and slightly enhance the local gas pressure outside the gap (e.g., Bryden *et al.* 1999; Crida *et al.* 2006). Dust grains that drift inwards with respect to the gas (see §3) can be trapped in this gas pressure maximum, creating a dense, concentrated ring of mm/cm-sized particles centered at ∼1.2–2.0 a_p (depending on the companion mass and the disk viscosity; Pinilla *et al.* 2012; Paardekooper & Mellema 2006). The properties of the disk interior to the gap depend strongly on the inward flow of material past the planet, which is partially tied to the planetary accretion efficiency (Lubow *et al.* 1999; Crida & Morbidelli 2007; Zhu *et al.* 2011). While some gas and small dust grains may reach the inner disk (Lubow & D'Angelo 2006; Dodson-Robinson & Salyk 2010), larger particles will be filtered from this flow by the gas pressure maximum (Rice *et al.* 2006; Zhu *et al.* 2012; Pinilla *et al.* 2012). This theoretical scenario makes some key observational

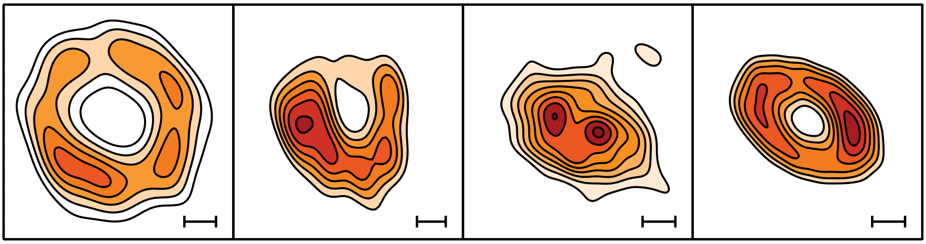

Figure 1. A selection of striking Submillimeter Array (SMA) 880 μm dust continuum images of transition disks: (*from left*) RX J1604.3−2130 (Mathews *et al.* 2012), SAO 206462 (Brown *et al.* 2009), GM Aur (Hughes *et al.* 2009), and LkCa 15 (Andrews *et al.* 2011b). A scale bar in the bottom right corner of each panel marks a projected physical distance of 40 AU for each disk.

predictions: disks interacting with a young planet (or planetary system) should exhibit a depletion of material at their centers and reduced accretion rates onto their host stars (depending on the planet accretion efficiency), with a narrow ring of large particles that trace the pressure maximum outside the gap (e.g., Wolf & D'Angelo 2005).

A category of young disks identified ∼25 years ago (Strom *et al.* 1989; Skrutskie *et al.* 1990) offers compelling empirical evidence for such planet-disk interactions. These so-called "transition" disks usually exhibit a relative deficit in their infrared spectrum, consistent with a diminished reservoir of warm dust within (at least) a few AU of the host star. However, it is difficult to robustly quantify these cavities with only unresolved spectrophotometric measurements, especially at optically thick infrared wavelengths. Interferometric observations in the radio were employed to first resolve the transition disks (Piétu *et al.* 2006; Hughes *et al.* 2007, 2009; Brown *et al.* 2008, 2009), which were found to exhibit limb-brightened "ring"-like morphologies in the dust continuum. Figure 1 illustrates these features for some particularly striking examples. Current limitations in sensitivity and resolution produce substantial selection biases on these radio observations, in favor of the most massive (i.e., brightest) disks with the largest cavities ($r \gtrsim 15$ AU for the nearest star-forming regions). Still, these transition disk morphologies are found to be surprisingly common: at least 1 in 4 disks in the bright half of the radio continuum luminosity distribution has a large, dust-depleted cavity (Andrews *et al.* 2011a).

Although depleted, these cavities are decidedly *not* empty. The currently available radio continuum data constrain the reduction of mm-sized grains to a factor $\gtrsim$100, but the presence of a deficit in the infrared spectrum is often a more stringent constraint on the dust content in the inner few AU (e.g., Andrews *et al.* 2011a; Espaillat *et al.* 2007; 2010). Most of the well-studied transition disk hosts are actively accreting gas (e.g., Fang *et al.* 2009; Espaillat *et al.* 2012), and direct tracers of small (∼μm-sized) dust grains (Dong *et al.* 2012; Follette *et al.* 2013) and molecular gas (e.g., Salyk *et al.* 2009; Rosenfeld *et al.* 2012) are being found well inside the radio-wave dust continuum rings.

Even at these early stages in the study of transition disks, their observational characteristics provide firm constraints on the physical mechanisms responsible for their origins. In most cases, the data are difficult to explain with either alternative disk evolution processes (see, e.g., Owen *et al.* 2011 and Birnstiel *et al.* 2012b regarding the issues with photoevaporation or particle growth, respectively) or more massive stellar/brown dwarf companions (Pott *et al.* 2010; Kraus *et al.* 2011). That said, a verified association of the observations with the planet formation theory through direct detections of faint, long-period companions located interior to the radio continuum rings would be beneficial (e.g., Huélamo *et al.* 2011; Kraus & Ireland 2012). Ultimately, I expect that ALMA observations will provide two key demographic constraints on planet formation through transition disks. First, the incidence of ring-like continuum emission geometries will offer a relatively unbiased estimate (compared to infrared colors) of the frequency and orbital distribution of giant planets at their formation epoch. And second, detailed probes of the gas content inside these dust rings, when coupled with accretion rates onto the host (and potentially direct imaging of the companions) can help estimate the mass distribution of these planets and will give new insights on their gaseous envelope accretion rates.

3. The Evolution of Disk Solids

The collisional evolution and migration of solids embedded in a gas-rich disk are fundamental processes in the core accretion model for planet formation. But building a quantitative, predictive theoretical framework for these processes is challenging, due to the complex interplay of the relevant physical mechanisms (coagulation, aerodynamics, turbulence, etc.) and enormous range of scales involved: solids need to grow $\sim$14 orders of magnitude in size (>40 orders of magnitude in mass) – from sub-μm grains to 1000 km embryos – within a few Myr. To further develop such a framework, we need to better understand two obstacles to the early stages of the planetary growth process. The first is related to the efficiency of growth by collisions: once dust grains grow to a certain size, their relative velocities can be sufficiently high that collisions are either non-productive (the particles bounce off one another; e.g., Zsom *et al.* 2010) or outright destructive (the particles fragment; e.g., Brauer *et al.* 2008, Birnstiel *et al.* 2010). The second is related to the rapid, inward migration of solids due to aerodynamic drag interactions with the gaseous reservoir in which they are embedded (radial drift; Weidenschilling 1977).

Numerical simulations of the evolution of solids in protoplanetary disks (informed by laboratory collision experiments) that account for these growth "barriers" make two robust, qualitative predictions that in principle can be tested with astronomical observations (e.g., Birnstiel *et al.* 2010a,b, 2011, 2012a): (1) the spatial distribution of solids should be radially size-sorted, such that larger particles are preferentially concentrated closer to the central stellar host; and (2) the abundance of $\sim$mm/cm-sized solids should be strongly depleted relative to the gas at large disk radii, due to the effects of radial drift (e.g., see also Takeuchi & Lin 2002, 2005; Brauer *et al.* 2007). Although the remote sensing of disk solids is limited to particles smaller than a few cm and stellocentric distances larger than $\sim$10 AU (presently), such observational data is readily scalable as an effective (albeit indirect) probe of the evolution of larger bodies in the inner disk.

The shape of the radio continuum spectrum has long been exploited to learn about the size distribution of disk solids (Beckwith & Sargent 1991). For an optically thin medium in the Rayleigh-Jeans limit, the radio spectrum scales like $I_\nu \propto \nu^{2+\beta}$, where β is the spectral index of the dust opacities ($\kappa_\nu \propto \nu^\beta$). For reference, $\beta \approx$ 1.7-2.0 in the ISM (Hildebrand 1983; Finkbeiner *et al.* 1999), but is only $\sim$0.5-1.0 in the integrated spectra of protoplanetary disks (e.g., Ricci *et al.* 2010a, 2010b). Draine (2006) demonstrated that, for a wide range of mineralogical compositions, a lower β is produced by a more top-heavy grain size distribution (see also Miyake & Nakagawa 1993; D'Alessio *et al.* 2001). However, the global, integrated β measurements derived from unresolved photometry offer only relatively weak empirical constraints on detailed models of particle evolution (Birnstiel *et al.* 2010b). The potential for quantitative development of these models instead relies on spatially resolved constraints on the radio colors – i.e., measurements of the $\beta(r)$ profile – to track how the particle size distribution varies as a function of the local physical conditions in the disk (e.g., Isella *et al.* 2010; Guilloteau *et al.* 2011).

Such measurements are notoriously challenging, since they require quality interferometric datasets with high sensitivity, resolution, and fidelity over a wide range of observing

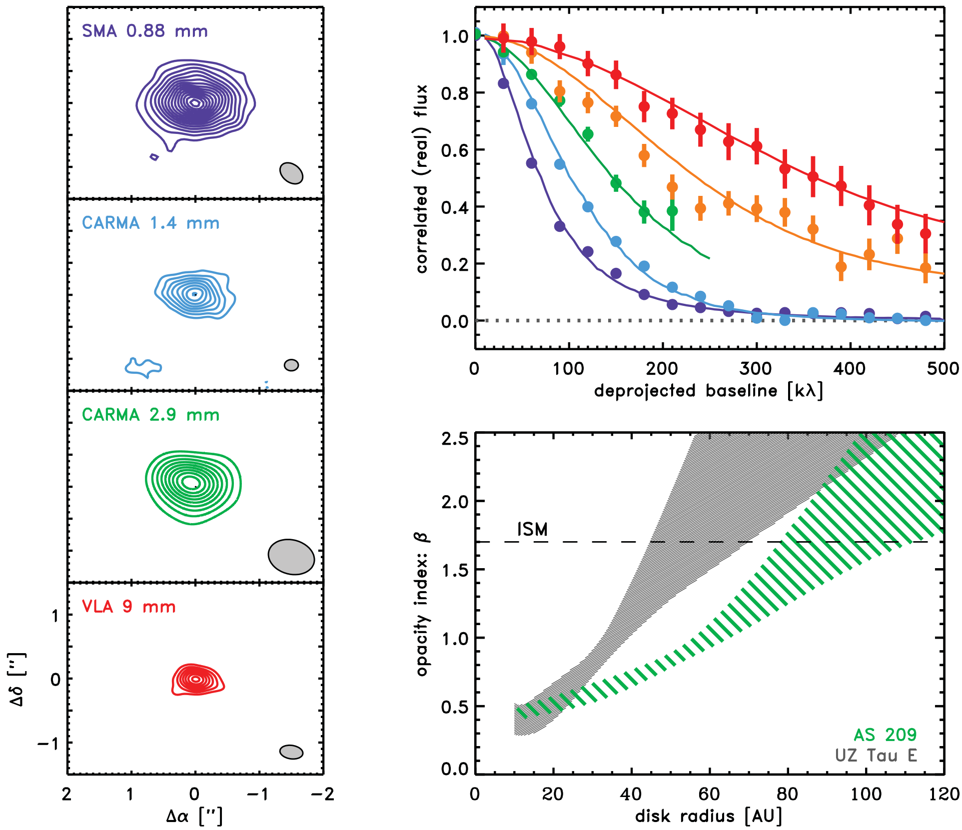

Figure 2. (*left*) A sequence of dust continuum images of the UZ Tau E disk at different radio wavelengths (adapted from Harris *et al.* 2013). (*top right*) The normalized, deprojected visibility profiles for the UZ Tau E disk continuum emission, where colors correspond to different observing wavelengths: (*from left to right*) 0.88, 1.4, 2.9, 8.0, and 9.8 mm. This panel demonstrates unequivocally that the size of the dust emission is anti-correlated with the observing wavelength. (*bottom right*) The derived radial profile of the dust opacity index, $\beta(r)$, for the UZ Tau E (*solid*) and AS 209 (*hatched*) disks (the regions correspond to 95% confidence intervals), from Harris *et al.* (2013) and Pérez *et al.* (2012), respectively. In both cases, the increasing $\beta(r)$ is consistent with the size-sorting of disk solids expected from models of particle growth and radial drift.

frequencies. However, an ongoing key project at the upgraded VLA ("Disks@EVLA", PI Claire Chandler) is facilitating a vast improvement in this work by providing excellent high-resolution observations of the dust continuum emission from disks at cm wavelengths. An illustrative example from this project – the disk around UZ Tau E – is highlighted in Figure 2. In a recent analysis by Harris *et al.* (2013), continuum emission from this disk was resolved at five distinct wavelengths from 0.88 to 9.8 mm, and was found to exhibit a clear anti-correlation between the spatial extent of the continuum emission (i.e., the apparent size) and the observing wavelength. Since thermal emission peaks at a wavelength comparable to the representative particle size, these data hint that larger solids are preferentially concentrated near the central host star. That behavior was quantified by modeling the radial optical depth profile at each wavelength, and then fitting a power-law spectrum at each radius to derive $\beta(r)$ (see Isella *et al.* 2010 for details). This $\beta(r)$ profile (Fig. 2; bottom right) shows a pronounced increase, confirming the presence of a radial variation in the particle size distribution. A similar constraint on $\beta(r)$ for the AS 209 disk is also shown for reference (see Pérez *et al.* 2012). A comparison

https://doi.org/10.1017/S1743921313007977 Published online by Cambridge University Press

to the theoretical models of Birnstiel *et al.* suggest that these data are consistent with particle growth by more than an order of magnitude, and can be readily explained by a growth process that is limited by radial drift (as opposed to turbulent fragmentation). Moreover, the larger scale Disks@EVLA project is finding that this firm evidence for the radial size-sorting of disk solids is a *generic feature* of protoplanetary disks. While that unfortunately implies that one cannot measure the dust surface densities, Σ_d, using data at only a single wavelength, it does suggest that we have an exciting opportunity to empirically characterize the formation of planetesimals in these disks.

According to simulations of particle evolution, the observational signature described above should be accompanied by a radial variation in the dust-to-gas mass ratio, ζ, such that the outer disk is selectively depopulated of mm/cm-sized particles. In essence, $\zeta(r)$ should be a decreasing function. Unfortunately, we do not know how to robustly measure disk gas densities (see §4), so a *direct* observational constraint on $\zeta(r)$ is not possible. Nevertheless, we can employ an analogous technique to the one described above to indirectly search for a non-constant $\zeta(r)$ by comparing the spatial distributions of gas and dust tracers. When the apparent sizes of a disk are measured in a CO rotational transition and the neighboring dust continuum, observers typically find a notable discrepancy: the molecular gas appears much more spatially extended than the dust (e.g., Piétu *et al.* 2007; Isella *et al.* 2007). However, an interpretation of this discrepancy requires caution: bright gas tracers (like CO emission lines) are optically thick, so they are sensitive to very small amounts of material in the outer disk, whereas the dust continuum emission is optically thin, and therefore is subject to sensitivity or model interpretation issues at large disk radii (see Hughes *et al.* 2008 for a discussion of these issues). With a sufficiently sensitive dataset, a modeling procedure based on a logical negation can be used to indirectly infer a decreasing $\zeta(r)$: (1) construct a model structure that reproduces the observations of dust; (2) assume a constant ζ at all radii; (3) simulate the corresponding model of the molecular line emission; (4) compare to observations; (5) invariably find that the model line emission is much too compact, and therefore infer that assumption (2) is incorrect – so, $\zeta(r)$ must be a decreasing function. This is a difficult task, requiring extensive radiative transfer modeling, but there is mounting evidence that indeed confirms the expected gas–dust size discrepancy (by a factor of $\sim$2-5 in radius) in some disks, providing strong, qualitative support for the predictions of radial drift models (Panić *et al.* 2009; Andrews *et al.* 2012; Rosenfeld *et al.* 2013b). In the near future, I expect that the combination of this approach to characterize $\zeta(r)$ with the constraints on $\beta(r)$ described above will offer new insights on the general migration of disk solids.

4. Toward New Constraints on Gas Disk Structures

Ultimately, in the context of constraining the initial conditions available for giant planet formation, we want to observationally infer gas densities in protoplanetary disks. However, this is a remarkably challenging measurement. The absence of a permanent dipole moment for the H_2 molecule means that the primary constituent of the gas reservoir is effectively "dark." To date, most studies have depended on dust as an overall density tracer: but given the discussion in §3 regarding the mounting evidence for spatial variations in the particle size distribution and dust-to-gas ratio, this is clearly not a reliable approach. We could instead rely on trace molecular species as a proxy for H_2, but in general a given molecular abundance (relative to H_2) is not known *a priori.* Even with guidance from a chemical network model, the optically thin (usually isotopologue) emission lines for a given species are quite weak, and will require a considerable time investment even with ALMA. Moreover, a self-consistent model of spatially resolved

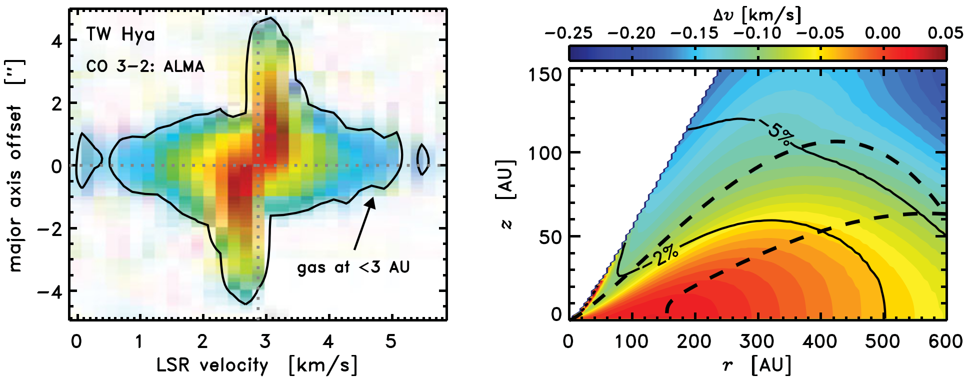

Figure 3. (*left*) A position-velocity diagram for the CO $J = 3{-}2$ line in the TW Hya disk, made from ALMA science verification data. Since this disk is observed with a nearly pole-on orientation, the presence of emission wings extending a few km s^{-1} from the systemic velocity is a clear indication of gas residing inside the inferred dust cavity even though the angular resolution of the data is much larger than the cavity size (see Rosenfeld *et al.* 2012). (*right*) A two-dimensional map of the deviations from the Keplerian velocity for a nominal structure model of the HD 163296 disk, based on an analysis of ALMA science verification observations of a range of CO emission lines (Rosenfeld *et al.* 2013a). Dashed contours mark the CO emission region, indicating that non-Keplerian motions caused by geometric and pressure effects (and perhaps self-gravity) in the disk atmosphere are on the scale of the observational spectral resolution. In the future, such kinematic effects can be used to help better constrain the gas structure.

line emission needs to consider the complex inter-dependence of the multi-dimensional temperature and density structures (e.g., see Rosenfeld *et al.* 2013a).

Admittedly, this paints a somewhat bleak picture for the prospects of measuring gas densities. At least for large samples, that might be valid. However, there is an incremental path toward achieving this goal for individual disks. The first step is to try and reconstruct the temperature distribution of the gas, as a function of both radius and height in the disk. In principal, this can be achieved in two (complementary) ways: (1) spectral mapping of a sequence of line ratios, using transitions with a range of optical depths to probe the temperatures at a range of different layers in the disk atmosphere (e.g., Dartois *et al.* 2003); and (2) locating molecular depletion boundaries directly (e.g., Qi *et al.* 2011; see also the contribution from Qi in this volume). Such observations would then need to be coupled to a suite of optically thin lines (e.g., a $C^{18}O$ ladder), and the structure iterated to ensure a physically consistent coupling between the gas densities and temperatures. To my knowledge, this has not yet been convincingly accomplished. But, in principal, the molecular excitation, radiative transfer, and chemical network tools required for the job are all available or under active development: it is all just a matter of accumulating the data with sufficient quality and resolution before putting them to use.

In most analyses of spatially and spectrally resolved line data, the co-dependence of the disk velocity field and gas structure is a complication that is often left untreated (not for invalid reasons: the current data does not typically warrant addressing it). But the close relationship between disk structure and kinematics will hopefully provide some mutually beneficial opportunities in the ALMA era (see Figure 3). One such example is the exploitation of the regular differential (Keplerian) rotation of the disk to probe gas content at spatial scales much smaller than the angular resolution affords: in effect, a kinematic super-resolution based on the wings of an emission line. So far, this approach has been used to assess whether gas is present inside the dust cavities of transition disks (see §2; Dutrey *et al.* 2008; Rosenfeld *et al.* 2012), although it could certainly be used in more general cases to probe physical conditions in the inner regions of a disk. Another example would be to take advantage of the small deviations from Keplerian rotation expected for emission lines that form high above the disk midplane, due to both geometric and pressure effects (and potentially self-gravity; see Rosenfeld *et al.* 2013a), to better understand the vertical distribution of gas densities and temperatures; in effect, to use kinematics as an additional constraint when constructing a gas structure model.

5. Summary

The anticipation of mature ALMA operations comes at a dynamic time in circumstellar disk research. This review highlighted a few key subjects being pursued in this field, including: (1) the use of disk structures as signposts of early giant planet formation; (2) the mounting evidence for the observable signatures of the growth and migration of disk solids; and (3) some prospects for better characterizing the gas content of these disks, in the context of initial conditions for planet formation. The results reviewed above should be considered the first steps in an era of new precision – and probably surprises – in the development of an observational component to the study of planet formation.

I would like to thank the organizers for inviting me to give this review, and to acknowledge the useful input and hard work of my colleagues that participated in much of the analysis and results that are presented here, especially: Katherine Rosenfeld, Robert Harris, David Wilner, Meredith Hughes, Til Birnstiel, Catherine Espaillat, Joanna Brown, Paola Pinilla, Geoff Mathews, and the Disks@EVLA team.

References

Alibert, Y., Mordasini, C., Benz, W., & Winisdoerffer, C. 2005, *A&A*, 434, 343
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2009, *ApJ*, 700, 1502
Andrews, S. M., *et al.* 2011, *ApJ*, 732, 42 (2011a)
Andrews, S. M., Rosenfeld, K. A., Wilner, D. J., & Bremer, M. 2011, *ApJ*, 742, L5 (2011b)
Andrews, S. M., *et al.* 2012, *ApJ*, 744, 162
Baruteau, C., & Masset, F. 2013, *Tides in Astronomy and Astrophysics, Lecture Notes in Physics*, eds. Souchay, Mathis, & Tokieda (Springer-Verlag: Berlin), 861, 201
Beckwith, S. V.W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, *AJ*, 99, 924
Beckwith, S. V.W. & Sargent, A. I. 1991, *ApJ* 381, 250
Birnstiel, T., Dullemond, C. P., & Brauer, F. 2010, *A&A*, 513, 79 (2010a)
Birnstiel, T., *et al.* 2010, *A&A*, 516, L14 (2010b)
Birnstiel, T., Ormel, C. W., & Dullemond, C. P. 2011, *A&A*, 525, 11
Birnstiel, T., Klahr, H., & Ercolano, B. 2012, *A&A*, 539, 148 (2012a)
Birnstiel, T., Andrews, S. M., & Ercolano, B. 2012, *A&A*, 544, 79 (2012b)
Brauer, F., *et al.* 2007, *A&A*, 469, 1169
Brauer, F., Dullemond, C. P., & Henning, T. 2008, *A&A*, 480, 859
Brown, J. M., Blake, G. A., Qi, C., Dullemond, C. P., & Wilner, D. J. 2008, *ApJ*, 675, L109
Brown, J. M., *et al.* 2009, *ApJ*, 704, 496
Bryden, G., Chen, X., Lin, D. N.C., Nelson, R. P., & Papaloizou, J. C.B. 1999, *ApJ*, 514, 344
Crida, A., Morbidelli, A., & Masset, F. 2006, *Icarus*, 181, 587
Crida, A. & Morbidelli, A. 2007, *MNRAS*, 377, 1324
D'Alessio, P., Calvet, N., & Hartmann, L. 2001, *ApJ*, 553, 321
Dartois, E., Dutrey, A., & Guilloteau, S. 2003, *A&A*, 399, 773
Dodson-Robinson, S. E. & Salyk, C. 2011, *ApJ*, 738, 131
Dong, R., *et al.* 2012, *ApJ*, 750, 161
Draine, B. T. 2006, *ApJ*, 636, 1114
Dutrey, A., *et al.* 2008, *A&A*, 490, L15

Espaillat, C., *et al.* 2007, *ApJ*, 670, L135
Espaillat, C., *et al.* 2010, *ApJ*, 717, 441
Espaillat, C., *et al.* 2012, *ApJ*, 747, 103
Fang, M., *et al.* 2009, *A&A*, 504, 461
Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 1999, *ApJ*, 524, 867
Follette, K. B., *et al.* 2013, *ApJ*, 767, 10
Guilloteau, S., Dutrey, A., Piétu, V., & Boehler, Y. 2011, *A&A*, 529, 105
Harris, R. J., *et al.* 2013, *ApJ*, submitted
Hildebrand, R. H. 1983, *QJRAS*, 24, 267
Huélamo, N., Lacour, S., Tuthill, P., Ireland, M., Kraus, A., & Chauvin, G. 2011, *A&A*, 528, L7
Hughes, A. M., *et al.* 2007, *ApJ*, 664, 536
Hughes, A. M., Wilner, D. J., Qi, C., & Hogerheijde, M. R. 2008, *ApJ*, 678, 1119
Hughes, A. M., *et al.* 2009, *ApJ*, 698, 131
Ida, S., & Lin, D. N.C. 2004, *ApJ*, 604, 388
Ida, S., & Lin, D. N.C. 2005, *ApJ*, 626, 1045
Isella, A., Testi, L., Natta, A., Neri, R., Wilner, D., & Qi, C. 2007, *A&A*, 469, 213
Isella, A., Carpenter, J. M., & Sargent, A. I. 2009, *ApJ*, 701, 260
Isella, A., Carpenter, J. M., & Sargent, A. I. 2010, *ApJ*, 714, 1746
Kraus, A. L., Ireland, M. J., Martinache, F., & Hillenbrand, L. A. 2011, *ApJ*, 731, 8
Kraus, A. L. & Ireland, M. J. 2012, *ApJ*, 745, 5
Lubow, S. H., Seibert, M., & Artymowicz, P. 1999, *ApJ*, 526, 1001
Lubow, S. H. & D'Angelo 2006, *ApJ*, 641, 526
Kley, W. & Nelson, R. P. 2012, *ARAA*, 50, 211
Mathews, G. S., Williams, J. P., & Ménard, F. 2012, *ApJ*, 753, 59
Mordasini, C., Alibert, Y., Benz, W. 2009, *A&A*, 501, 1139
Owen, J. E., Ercolano, B., & Clarke, C. J. 2011, *MNRAS*, 412, 13
Paardekooper, S.-J., & Mellema, G. 2006, *A&A*, 453, 1129
Panić, O., Hogerheijde, M. R., Wilner, D., & Qi, C. 2009, *A&A*, 501, 269
Papaloizou, J. C.B., Newlson, R. P., Kley, W., Masset, F. S., & Artymowicz, P. 2007, in *Protostars & Planets V*, eds. B. Reipurth, D. Jewitt, & K. Keil (Univ. Arizona Press: Tucson), 655
Pérez, L. M., *et al.* 2012, *ApJ*, 760, L17
Piétu, V., Dutrey, A., Guilloteau, S., Chapillon, E., & Pety, J. 2006, *A&A*, 460, L43
Piétu, V., Dutrey, A., & Guilloteau, S. 2007, *A&A*, 467, 163
Pinilla, P., Benisty, M., & Birnstiel, T. 2012, *A&A*, 545, 81
Pott, J.-U., *et al.* 2010, *ApJ*, 710, 265
Qi, C., *et al.* 2011, *ApJ*, 740, 84
Rice, W. K.M., Armitage, P. J., Wood, K., & Lodato, G. 2006, *MNRAS*, 373, 1619
Ricci, L., *et al.* 2010, *A&A*, 512, 15 (2010a)
Ricci, L., Testi, L., Natta, A., & Brooks, K. J. 2010, *A&A*, 521, 66 (2010b)
Rosenfeld, K. A., *et al.* 2012, *ApJ*, 757, 129
Rosenfeld, K. A., *et al.* 2013, *ApJ*, 774, 16 (2013a)
Rosenfeld, K. A., *et al.* 2013, *ApJ*, 775, 136 (2013b)
Salyk, C., Blake, G. A., Boogert, A. C. A., & Brown, J. M. 2009, *ApJ*, 699, 330
Skrutskie, M. F., *et al.* 1990, *AJ*, 99, 1187
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, *AJ*, 97, 1451
Takeuchi, T. & Lin, D. N.C. 2002, *ApJ*, 581, 1344
Takeuchi, T. & Lin, D. N.C. 2005, *ApJ*, 623, 482
Weidenschilling 1977, *MNRAS*, 180, 57
Wolf, S. & D'Angelo, G. 2005, *ApJ*, 619, 1114
Zhu, Z., Nelson, R. P., Hartmann, L., Espaillat, C., & Calvet, N. 2011, *ApJ*, 729, 47
Zhu, Z., Nelson, R. P., Dong, R., Espaillat, C., & Hartmann, L. 2012, *ApJ*, 755, 6
Zsom, A., Ormel, C. W., Güttler, C., Blum, J., & Dullemond, C. P. 2010, *A&A*, 513, 57

Discussion

Gaidos: Are any of the lines that ALMA can access so intrinsically narrow that pressures, and hence gas mass surface densities, could be estimated from pressure broadening?

Andrews: No. So long as the disk is less massive than the stellar host, the gas densities are always sufficiently low that thermal broadening will always dominate pressure broadening (by orders of magnitude) for any reasonable molecular cross section.

Rafikov: You find high values of the opacity index β, at the level of $\beta \gtrsim 3$, in the outer parts of the disk. What material properties of grains can give rise to such behavior?

Andrews: This is essentially an artifact of the modeling process, and not necessarily produced by a real dust population. In practice, any estimate of β increases rapidly at large radii where we do not detect any cm-wave emission with the VLA.

Lin: Is there any inconsistency between the rarity of companions around young stars from the NICI survey and the detection of transitional disks around 1/3 of the systems?

Andrews: Not yet, but I agree that the statistics are uncomfortably close to a conflict. If we consider the total population of a young cluster (rather than the biased samples imaged so far) – including the apparently disk-less members – the transition disk fraction seems consistent with the limits placed on gas giant planets at large radii from direct imaging surveys (i.e., $\lesssim$5–10%). However, if future surveys with ALMA end up finding a lot more transition disks, then we would need to re-consider the planet-disk interaction hypothesis as a primary cause for the observed disk structures. One mechanism worth considering is the potential for migration to alleviate the tension: perhaps the planets that open the cavities will later migrate to smaller stellocentric distances.

Dodson-Robinson: Have there been any attempts to model the evolution of the gas/solids ratio in disks based on grain growth and even planetesimal formation models?

Andrews: This is really an ongoing effort by the community, but I can refer you to the preliminary models by Birnstiel *et al.* (2012) as a good place to start. I expect a great deal more work in this direction in the coming few years.

Pudritz: Do we have any observational constraints on the growth timescales for dust in disks?

Andrews: The short answer is "not really." It is clear that large particles (mm/cm sizes) have already formed in ~Myr-old disks, but pinpointing timescales at finer time resolution is a challenge. Theoretical models expect such growth to be very fast indeed, so the data are not quite yet offering robust constraints on this question.

Hales: You showed an example of a disk that showed different morphologies in the 1.3 mm SMA map compared to your recent 450 μm ALMA data (a central peak versus a ring at 1.3 mm). Could you please comment on this differentce?

Andrews: I believe this is an optical depth effect, where the inner disk is optically thick in the ALMA Band 9 data, but not in the SMA 1.3 mm data: but this has yet to be examined quantitatively. (Note: these data are not discussed or displayed in this review. The question and response are included for the sake of completeness.)