Problems in Circumstellar Disks and Planet Formation

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1. Introduction

This white paper poses fundamental questions about planet formation and suggests some approaches to address them. The last decade and a half has provided the proof that planets with masses from about 5 M_{Earth} to 20 $M_{Jupiter}$ encircle other stars (e.g. Butler et al. 2006). In the next decade, the lower limit of that range will decrease yet further and exciting work to determine the composition and habitability of planets will begin. Even if the phase space of planetary architectures is well explored, however, it is still important to understand how the remarkable variety of systems came to be. This requires that we study the early history of planets and how they interact with their natal environment, the circumstellar disk.

Basic questions about circumstellar disks as the source of raw materials for planets remain unanswered. This uncertainty permeates models for planet formation. In many cases, the uncertainty can be parameterized, but obtaining observations of fundamental quantities is of key importance.

2. Do most stars possess disks massive enough to form planets?

For a complete description, we must measure the mass in disks as a function of radius and time and search for disk gaps cleared as planets form. Masses are measured from single-dish and interferometric submm observations of CO (or other trace gases) and of dust continuum. The major uncertainties in the masses result from unknown dust opacities, gas-to-dust ratios, and disk structures. Source-to-source comparisons are probably more accurate than absolute masses, but changes in the grain size distribution and/or composition add uncertainties to relative measurements. There is no way to measure the size distribution for grains $\gtrsim$1 cm

A combination of approaches over the next decade will improve mass estimates and survey a wider range of targets in different star forming environments. The *Atacama Large Millimeter Array (ALMA)* will probe gas tracers at higher sensitivity and spatial resolution, and will detect sources at greater distances, than the current generation of submm arrays. The *Herschel Space Observatory* will observe gas forbidden lines from cool disk regions but will still have to rely upon disk chemistry models to determine masses.

Gas dominates the mass of disks, but the dominant species is the typically unobservable molecular hydrogen. The *James Webb Space Telescope (JWST)* could, in principle, observe lines from warm molecular hydrogen directly, but the low resolution of its mid-infrared spectrometer limits the phase space of column densities it can probe. The high optical depth of disks even at 28 μm and cool midplane temperatures may make it difficult to measure H_2 in any circumstance in dense disks at 5–10 AU from their stars. However, a mid-infrared spectrometer with high spectral resolution in space would contribute important direct molecular hydrogen measurements. The warmer inner disks would have their gas masses measured directly for the first time. A Far-UV space spectrometer would sensitively measure total line-of-sight column densities of H_2, even at cold temperatures, against the stellar continuum (e.g. Roberge et al. 2001). By combining these sets of data, total gas masses could be calculated. Calibrating the H_2/CO ratio in disks of varying temperatures, rather than accepting the dense molecular cloud value at all disk ages, would yield much greater confidence in disk masses derived from gas tracers.

Disk mass may also vary as a function of star formating region, stellar density or other factors. Surveys of disk mass will have to probe a large sample to determine which variables matter. With robust means of measuring disk masses will come robust determinations of disk lifetimes as a function of stellar spectral type and age.

3. How is material distributed radially and vertically in the disk?

The surface density of material controls the timescales for planet formation (e.g. Desch 2007). The temperature and viscosity of the disk control the transport of solids and therefore the composition of the material that can form planets (Ciesla 2008). Ideally one would like to know the surface density profile; its radial dependence has implications for disk evolution mechanisms and planetary growth calculations.

Imagine a set of disks that can be well resolved spatially and kinematically. The ideal spatial resolution would be enough to separate the inner (warm enough to sublimate ice) and outer (beyond the ice-line) portions of the disk. If this scale is about 5 AU for a solar-type star, then at the distance to the nearest very young stars in say, Ophiuchus, at 140 pc, the required spatial resolution is 18 mas (for two resolution elements interior to 5 AU). This is four times better than *JWST* but is very well matched to adaptive optics in the near-infrared on a ground-based *Extremely Large Telescope (ELT)*. The diffraction limit of a 25 m telescope at K-band is 18 mas. Direct imaging in scattered light at near-infrared wavelengths can constrain the radial extent, scale height, and amount of flaring of the disk.

The ideal kinematic resolution would allow measurement of sub-Keplerian velocities within and beyond our fiducial 5 AU boundary, that is, with a precision of 10km/s or better. Gas transitions, from the near-infrared out to submm wavelengths, will all contribute to the total picture of disk structure.

Near-infrared absorption studies can determine the amount of warm gas (e.g. Rettig et al. 2006). Emission by gas lines such as CO fundamental and water in the mid-infrared that are resolved spectrally (e.g. Salyk et al. 2008) can define the motions of the gas as a function of radius by modeling of the line profiles. The infrared studies have marginal sensitivity with today's 10 m class telescopes, require high spectral resolution for resolving line kinematics, and would therefore be best done with an ELT. Submm interferometry with *ALMA* can provide the distribution of cold gas and its kinematics (e.g. Qi et al. 2006).

CO self-shielding may produce the oxygen isotope ratios in solar system meteorites, which show mass-independent fractionation as opposed to the expected mass-dependent fractionation line (Lyons & Young 2005). The common $C^{16}O$ remains optically thick to stellar or external UV throughout the disk while the less common $C^{17}O$ and $C^{18}O$ can be dissociated in the optically thin upper layers of the disk. For these oxygen isotopes then to reach the meteoritic material where they are observed today, they have to be mixed into the disk interior and incorporated into water or silicates.

Confirmation of this scenario would not just explain puzzling solar system observations. It would also allow direct measurements of the vertical mixing, which takes the dissociated C and O atoms from the surface of the disk into the midplane. It would also trace radial mixing, which takes the ^{18}O enriched ice and distributes it to smaller radii, where it can be sublimated and observed as OH or water emission.

4. How does disk material dissipate?

From what we know already, many stars of age <1 Myr have disks with substantial gas masses and most of age >10 Myr do not. The small number of so-called transitional objects, i.e. those that appear to have lost some but not all of their disk material, are relatively rare, which suggests that the timescale for dissipation is rapid. Two plausible scenarios are currently under consideration for disk clearing. Perhaps planet formation itself clears the disk. Second, some success has been achieved in models with viscous accretion plus photoevaporation, both by an external irradiator such as a massive O star, or internally by the young star itself.

Extreme UV (λ <912Å) is most effective at photoevaporation, followed by far-UV photons. The uncertainty in the flux of extreme-UV allows a lot of flexibility in the models, but there may be a real problem in producing enough EUV for photoevaporation at low accretion rates. FUV observations of young stars are definitely needed for accurate calculation of disk loss rates (Alexander et al. 2005). This will require a space-based mission significantly more sensitive than *FUSE*.

The direct effects of photoevaporation or planets opening gaps ought to be visible in the structure of the disk. The measurements described in §3 are therefore all relevant to tracing the changes in disk structure that occur as material is accreted or evaporated. Alexander & Armitage (2007) suggest that a combination of disk mass and accretion rate measurements could show whether photoevaporation is at work. If photoevaporation opens a gap in the disk, this should be visible in high spatial resolution submm or scattered light images. Although accretion drops to very low levels or stops in a few million years, it is important to measure how much gas remains; small amounts of gas can affect the dynamics of growing terrestrial planets, e.g., by damping their eccentricities.

5. How do disks and planetesimals interact?

In order to form terrestrial planets or cores of giant planets, solids must grow from micron-sized to Earth-mass sized objects via gentle collisions. Yet, the interaction of solid bodies of certain sizes with disk gas causes them to rapidly move inward to the point where they would be evaporated or accreted onto the star. The problem is severe for the meter-sized rocks that presumably form quickly in disks. From regions several AU in size in only tens of years, these objects should be quickly moved to the inner disk (e.g. Cuzzi & Weidenschilling 2006). The problem is also severe for planetary embryos that form spiral density waves in the gas. How is it then that solids ever build into larger bodies?

Simulations use turbulence to reduce inward drift rates and suggest concentration processes to make solids grow to 100 – 1000 km sizes quickly. Observationally, determining turbulent gas motions as a function of distance from the star would quantify the effects in models. This could be approached with a combination of high spatial and spectral resolution to look for deviations from Keplerian motion as a function of radius. Both *ALMA* and *ELT* would play important roles. The disk viscosity, which is tuned in accretion models to match accretion rates, is not yet directly measured. The width of gaps opened by planets depends on viscosity, and could be measured with high spatial resolution imaging with the *ELT*. The migration rate depends on the spatial and thermal structure of the disk, making the observations of §3 again relevant.

If young disks do have giant planets already embedded within them, as the models of Boss (1997) suggest, the kinematics of the gas will be altered. Gas rotation will be modified from strictly Keplerian by interaction with the planets. With sufficient signal-to-noise and spectral resolution, these could be measured.

Evidently, the planets in our solar system did not migrate much from their original formation locations. However, we think the hot planets in periods of 0.5 to a few days migrated substantially. The answer to why the formation outcomes of these systems are so fundamentally different lies in how very large solids, i.e. planets, interact with disks. There was some real piece of physics that operated on the hot Jupiters that did not operate on our Jupiter. Determining the temperature and density and 3-dimensional structure of protoplanetary disks will inform the various theoretical models that seek to understand planetary migration.

6. How do planets obtain their compositions and volatiles?

The Solar System planets evidently vary greatly in their surface and bulk compositions, from dry to water-rich and from gas-rich to ice-rich. Simple consideration of temperature suggests that there is an "ice-line" somewhere in the disk, i.e. the point at which the temperature drops below $\sim$150 K so that water ice is stable against sublimation. In fact, there is unlikely to be a single ice line as different vertical heights in the disk will have different temperatures and pressures so that the point of ice stability will be both a function of radius and height. Furthermore, as the star evolves and the accretion rate changes, these points will move. Planetesimals inside the ice-line are expected to be fairly dry while those outside, wet. Other important chemical changes happen at the ice-line and elsewhere in the disk. How planetesimals of various compositions form and then mix will determine whether planets formed inside the ice-line are water rich.

There are no measurements of the ice-line. One can imagine several observational approaches. Line of sight mid-infrared absorption spectroscopy in disks whose geometry is measured in resolved imaging might show, on average, where ice begins. Measurements of OH or water vapor lines as a function of radius would indicate where ice sublimates. These species have lines in the near and mid-infrared, where one could apply the technique of "spectroastrometry" on the *ELT* (Pontoppidan et al. 2008). Combining high spectral resolution for detailed line profiles and high spatial resolution using adaptive optics, the location and kinematics of gas lines can be determined. Large aperture is also necessary for pure detection of weak line fluxes.

If giant planets form by core-accretion, then they may form more efficiently outside the ice-line. The combination of finding the ice-line and detecting young planets (a subject outside the scope of this white paper) would be a test of core-accretion theory.

How the carbon content of a protoplanetary disk is distributed amongst dust, CO, methane and PAHs can affect the ability to form planets of different composition. If methane ice is prevalent in the outer disk, it may be easier to form ice-giant planets like Neptune. CO may lock up oxygen that would otherwise form silicates, that in turn would more readily form planetesimals. Spatially resolved near-infrared spectroscopy of methane gas might determine the "methane ice-line." CO will be measured with *ALMA*. Ices could be seen in spatially resolved near-infrared scattered light images with the *ELT*.

7. Giant Impacts and Habitability

Giant impacts probably shaped our system's terrestrial planets: perhaps on Mercury to strip its mantle and leave the core observed today (Benz et al. 1988), on Mars to make its hemispheric crustal thickness asymmetry (Marinova et al. 2008), and on Earth to form the

Moon (Canup 2004). In the case of the Moon, geochemical evidence suggests a formation time $\gtrsim$50 Myr after the first solids formed in the Solar System. Since that time, there has not been an impact on Earth large enough to cause large scale mantle melting or total evaporation of the oceans. The absence of planet-scale impacts on Earth in the last 4 Gyr has allowed life to emerge and thrive.

After primordial gas is gone from disks, the remaining planet plus planetesimal system may be observed as a "debris disk." The debris is produced in the collisions and evaporation of planetesimals. To learn about the planetesimal content and collision rate and the composition of bodies during the final stages of planetary accretion, one must study the structure and composition of the debris disks. High spatial resolution observations of disk structure may reveal the locations of planetesimal belts. *HST* has already made exquisite observations, and *JWST* will undoubtedly make many more. To see the 1–4 AU scale of the terrestrial planets in our own solar system, however, requires the spatial resolution increase afforded by *ALMA*, an *ELT*, and also space-based exo-planet missions in either the visible or mid-infrared. To measure the composition of the dust, which presumably represents the composition of parent bodies, requires spatially resolved low spectral-resolution near-infrared spectroscopy. Solid state dust features such as olivine, water-ice, and organics all have broad near-infrared features. Spatially resolved mid-infrared spectroscopy will look for changing silicate mineralogy that would indicate different parent body compositions and processing.

8. Recommendations

The study of circumstellar disks from the proto-planetary through debris phases will require efforts with multiple techniques at many wavelengths. Protoplanetary disks become optically thick at some depth at most wavelengths; thus determining the true disk structure requires the careful combination of many pieces of evidence.

New capabilities mentioned in this white paper are summarized here:

- ELT
  - Extreme Adaptive Optics for Disk Imaging and Spatially Resolved Spectroscopy
  - R>100,000 near-infrared spectrometer (out to 5 μm)
- Mid-infrared space telescope for sensitive H_2 detection
- Far-UV space telescope
  - Sensitive photometry of FUV flux density
  - High spectral resolution for sensitive H_2 detection

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