Unlocking the Secrets of Planet Formation with Hydrogen Deuteride

The Uncertain Gas Mass of Planet-Forming Disks

Planets are born within disk systems (protoplanetary disks) that are predominantly molecular in composition with a population of small (sub-micron to cm sized) dust grains that represent the seeds of Earth-like planets. The most fundamental quantity that determines whether planets can form is the protoplanetary disk mass; forming planetary systems like our own requires a minimum disk mass of order ∼0.01 $M_\odot$ (i.e. the minimum mass solar nebula or MMSN; Weidenschilling, 1977; Hayashi, 1981). Estimates of disk masses are complicated by the fact that the molecular properties of dominant constituent, molecular hydrogen, lead it to be unemissive at temperatures of 10 – 30 K that characterizes much of the disk mass (Carmona et al., 2008).

To counter this difficulty astronomers adopt trace constituents as proxies to derive the H_2 mass. By far, the primary method is to use thermal continuum emission of the dust grains. At longer sub-mm/mm wavelengths the dust emission is optically thin probing the disk dust mass. With an assumed dust opacity coefficient, along with the ratio of the dust to gas mass, the disk gas mass is determined from the dust mass (Beckwith et al., 1990; Andrews & Williams, 2005). With this method the gas mass estimates range from 5 $\times 10^{-4} - 0.1$ $M_\odot$ (Williams & Cieza, 2011). However, a variety of sensitive observations have demonstrated that grains have likely undergone growth to sizes 1 mm to 1 cm (at least) in many systems (Testi et al., 2014). Thus the dust opacity is uncertain and the gas-to-dust ratio is likely variable (Draine, 2006; Isella et al., 2010). The alternative is to use rotational CO lines as gas tracers, but these are optically thick, and therefore trace the disk surface temperature, as opposed to the midplane mass. The use of CO as a gas tracer then leads to large discrepancies between mass estimates for different models of TW Hydrae, the closest gas-rich disk (from 5×10^{-4} $M_\odot$ to 0.06 $M_\odot$), even though each matches a similar set of observations (Thi et al., 2010; Gorti et al., 2011).

These uncertainties are well known with broad implications regarding the lifetime where gas is available to form giant planets, the primary mode of giant planet formation, either core accretion or gravitational instability in a massive disk (Hartmann, 2008), on the dynamical evolution of the seeds of terrestrial worlds (Kominami & Ida, 2004; Ida & Lin, 2004), and the resulting chemical composition of pre-planetary embroyos (Öberg et al., 2011). Given current uncertainties, we do not know whether our own solar system formed within a typical disk (Williams & Cieza, 2011). This extends beyond our planetary system as the frequency of extra-solar planet detections has been argued to require higher disk masses (Greaves & Rice, 2010; Mordasini et al., 2012).

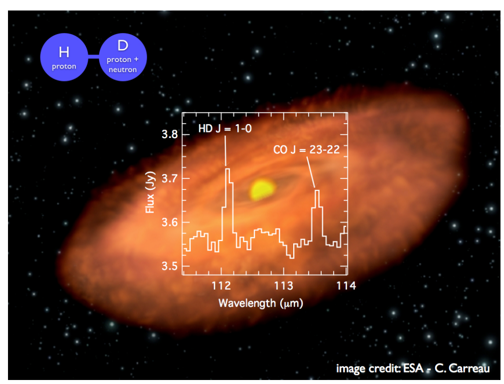

Figure 1: Herschel detection of Hydrogen Deuteride in the TW Hya protoplanetary disk superposed on an artist conception of a young gas-rich disk.

Far-IR Spectroscopy, HD, and Disk Gas Masses

Bergin et al. (2013), using the Herschel Space Observatory, detected the fundamental rotation transition of HD at 112 μm emitting from the TW Hya disk (shown in Fig. 1). The atomic deuterium abundance relative to H_2 is well characterized to be $3.0 \pm 0.2 \times 10^{-5}$ in objects that reside within $\sim$ 100 pc of the Sun (Linsky, 1998), such as TW Hydra. Unlike carbon monoxide, HD and H_2 are only weakly bound on the cold (T $\sim$ 10 – 20 K) dust grains that reside in the mass carrying disk midplane (Tielens, 1983). Thus HD resides primarily in the gas throughout the disk with a known abundance relative to H_2. With energy spacings better matched to the gas temperature and a weak dipole the lowest rotational transition of HD is a million times more emissive than H_2 for a given gas mass at 20 K. It is therefore well calibrated for conversion of its emission to the H_2 gas mass in the disk offering the best chance to derive accurate disk gas masses in regions that are potentially actively forming planets. In the case of TW Hya the gas mass is estimated to be > 0.05 $M_\odot$, or many times the MMSN.

Due to Herschel's limited lifetime the only other deep HD observations were obtained in the Cycle 1 program that resulted in the TW Hya detection. These observations, which are less sensitive than the TW Hya data, are shown in Fig. 2. For the most part, at this sensitivity limit, HD was not detected, although these disk are $\sim 3\times$ more distant than TW Hya. However, marginal detections ($> 3\sigma$) were obtained in DM Tau and GM Aur hinting at the future promise for a high impact survey with a future far-IR facility.

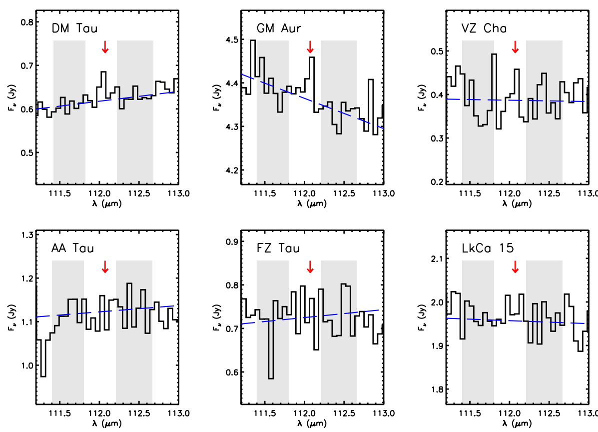

Figure 2: Results from the shallow survey of HD emission to be published by McClure et al. 2015, in prep.

A survey of HD emission, can only be enabled with a sensitive Far-IR observatory. To move beyond the $\sim$ 3 systems with accurate gas masses, and open up our understanding of planet formation, we need to detections in > 100 *disk systems. This will provide the missing - and grounding - information on the gas masses of planet-forming disks.* Such a survey of a hundred of the nearest systems can determine the timescales of planet formation, whether H_2 is present in debris disk systems, and set needed constraints for disk dynamical models. A large telescope might also *resolve* HD in the closest systems, allowing for constraints to be placed on the uncertain gas density profile.

Knowledge of the disk mass also breaks the degeneracy between disk mass and chemical abundance. As an example, Favre et al. (2013) used HD with $C^{18}O$ finding that the CO abundance is more than an order of magnitude below that in the dense ISM. This was explored more directly (Du, Bergin, and Hogerheijde 2015, in prep.) using a complete thermochemical model (Du & Bergin, 2014) to analyze CO isotopologue data but also Spitzer/Herschel observations of water vapor. This work finds that to match observations, the abundance of elemental oxygen and carbon must be reduced in the upper layers by orders of magnitude. This missing carbon and oxygen must reside as ices in the dense midplane locked inside pebbles or even planetesimals. This information is crucial as the Atacama Large Millimeter Array is now providing resolved images of gas tracers, such as CO and other species. Without HD in TW Hya we would assume that readily accessible gas tracers (e.g. CO, HCN, etc) suggest that the gas mass is low, while instead it is the beginnings of planet formation that is being revealed. Thus there is tremendous synergy of a future far-IR facility with ground based instruments; only the far-IR can provide this fundamental information.

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