1. Science aim/goal

Direct determination of protoplanetary disk gas masses using HD J = 1-0

2. (i) Scientific Importance:

The most fundamental quantity that determines whether planets can form is the protoplanetary disk mass. 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 the 10-30 K, which characterizes much of the disk mass. To counter this difficulty, astronomers use the thermal continuum emission of the dust grains or rotational lines of CO, both of which can be calibrated to trace the total gas mass. However, a variety of sensitive observations have demonstrated that grains have undergone substantial growth, making the determination via dust inherently uncertain. For instance, when CO lines are optically thick, they trace the disk surface temperature, as opposed to the midplane mass. 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, on the dynamical evolution of the seeds of terrestrial worlds, and the resulting chemical composition of pre-planetary embryos.

Bergin et al. (2013, Nature, 493, 644) using the Herschel Space Observatory, detected the fundamental rotation transition of HD at 112 μm emitting from the TW Hya disk (shown in Figure below). The atomic deuterium abundance relative to H_2 is well characterized and 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 HD emission to the H_2 gas mass. Due to Herschel's limited lifetime the only other deep HD observations obtained were in six disks, with the result of two additional marginal detections ($>3\sigma$; McClure et al. 2016, ApJ, submitted).

A survey of HD emission can only be enabled with a sensitive observatory operating at 112 μm. To move beyond the ~3 systems with accurate gas masses, and open up our understanding of planet formation, we need to detections in well over 100 disk systems. To give a sense of the scale in the state-of-the-art, the right panel of Figure 1 shows the disk frequency estimates from the IR excess. The method is to use stellar groups/clusters with known ages and determine fractions with excesses as the proxy for frequency. This is the state-of-the-art, but it represents the evolutionary timescale of *dust*, and not gas. No equivalent plot with significant accuracy exists for the gas, independent of chemical abundance uncertainties. For this type of study, tens to hundreds of stars within each group/cluster is needed, leading to a total of hundreds of sources is needed.

An HD emission survey will provide the missing - and grounding - information on the gas masses of planet-forming disks. Such a survey will determine the timescales of giant planet formation, understand the constraints on gas available for super-Earths/mini-Neptures, and set needed constraints for disk dynamical models. Knowledge of the disk mass also breaks the degeneracy between disk mass and chemical abundance. 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 measured lower abundances suggest it maybe that the beginnings of planet formation that is being revealed (Favre et al. 2013, ApJ). Thus there is tremendous synergy of a future far-IR facility with ground based instruments; only the far-IR can provide this fundamental information.

(ii) Measurements Required:

This measurement requires spectroscopy with a sensitivity significantly improved over Herschel. In the appendix we provide detailed model calculations as a function of stellar spectral type, disk dust mass, and gas mass. The models are grounded to the low end of the disk dust masses observed in clouds such as Taurus. At minimum we would need to observe down to a dust to gas mass ratio of unity for the lower end of this mass distribution ($M_{dust} = 2 \times 10^{-5}\ M_{\odot}$). For the coldest and most common disk systems (M stars) and scaled to 150 pc this would be a flux of 4.5×10^{-19} W/m^2. A complete survey thus requires a 1sigma sensitivity of ~10^{-21} W/m^2 for at least 3-4σ detection of the line in these low mass and cold systems.

Furthermore, since HD emits at a wavelength where the star often has strong continuum emission from the dusty disk, it would be best to have high spectral resolution. There is a tradeoff but Herschel sets a minimum useful limit in that R ~ 1000 and somewhat higher resolving powers are important for a complete survey. Very high resolving power, heterodyne systems (R≥50,000) offer the added capability to resolve the line with is dominated by Keplerian rotation. Thus resolving the line would provide unique and extremely useful information on the radius of origin. However, this would best be done with a separate high-resolution instrument for the brightest systems isolated by a deeper survey performed with a direct detection instrument.

(iii) Uniqueness to 10μm to few mm wavelength facility:

There is an instrument proposed for SOFIA (HIRMES) that has the potential to be more sensitive than Herschel. This could make some progress and observe a few (10 – 30) bright systems. This would be very useful and allow for progress to be made on understanding the evolution of individual objects. This is the only other (potentially) existing capability at this wavelength regime. However, the atmospheric background is still significant even when flying at stratospheric heights, and the line sensitivity is orders of magnitude lower than what could be achieved from space. Thus a true survey requires a space-based platform. This cannot be done from the ground.

(iv) Longevity/Durability:

Science case will not be completed by other facilities.

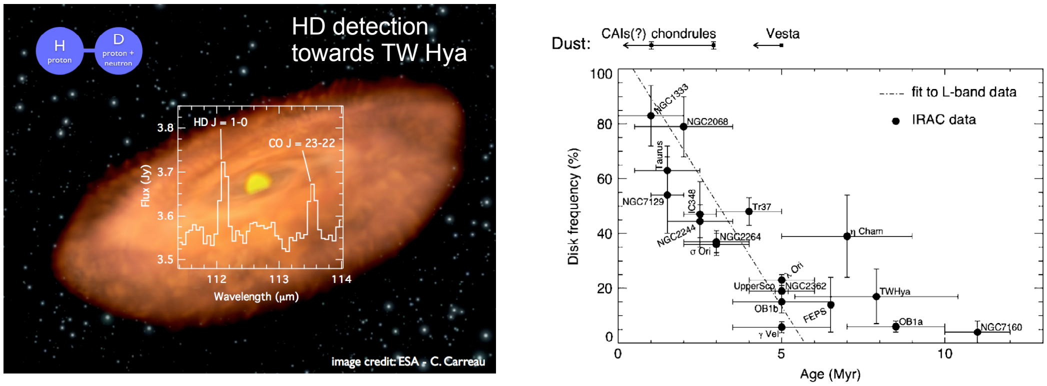

image credit: ESA - C. Carreau

Figure 1 ***(Left) Detection of HD in the TW Hya protoplanetary disk by Bergin et. al. 2013. (Right) State of the art for the disk dispersal time – based solely on dust measurements. Plot shows the fraction of stars with excesses in at Spitzer wavelengths (3.6 and 8 μm) as a function of age of the stellar group (figure from Pascucci and Tachibana et al. 2010 in Protoplanetary Dust: Astrophysical and Cosmochemical Perspectives, eds.: D. Apai, D. S. Lauretta, Cambridge University Press, 263-298).***

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	112	112	Hard requirement
Number of targets		500	500	Not stringent
Survey area	deg.^{2}	N.A.	N.A.	
Angular resolution	arcsec	3	< 1	3″ is based on sensitivity estimates from M. Bradford's calculations. Higher angular resolution is clearly preferred resolve the disks and to separate typical binaries. The nearest system is likely a few arc-seconds in size.
Spectral resolution	$\lambda/\Delta\lambda$	3,000	50,000	The mimimum resolving power matches Herschel. The desired value is needed to spectrally resolve the line in typical disks.
Bandwidth		100 km/s		
Continuum Sensitivity (1 σ)	μJy	-		
Spectral line sensitivity (1 σ)	W m^{-2}	10^{-21}	10^{-21}	
Signal –to-noise		5	10	
Dynamic range		100		
Field of Regard		Galactic plane +/-20 degrees		
Cadence				

5. Key references: (Optional, at most three, reviews preferred)

Bergin et al. 2013, Nature, 493, 644

Williams & Cieza 2011, ARA&A, 49, 67

Appendix

For the sensitivity calculations we use the protoplanetary disk thermochemical model of Du & Bergin 2014 (ApJ, 792, 2). The model assumes a stellar spectral type, and dust surface density distribution, along with an observationally motived radiation field (B stars are dominated by the stellar field, M stars have contributions from accretion luminosity in the ultraviolet). Within this framework, the vertical structure is calculated assuming hydrostatic equilibrium where we iteratively calculating the dust temperature and then the gas temperature based on heating-cooling balance and an extensive chemistry. The models presented here (Du et al. 2016, in prep.) are run over a range of total disk dust mass (0.25 to 2.0 × 10^{-4} $M_{\odot}$) which is grounded to the low end of the observed distribution of dust mass in Taurus (Williams and Cieza 2011). The results, are shown in Figure 2, provide the predicted HD flux at 112 µm as a function of disk dust mass (labelled in each figure), the stellar type, and the dust-to-gas mass ratio. For a fixed dust gas of the disk, a lower dust-to-gas mass ratio means a higher gas mass. The model disks are assumed to have an outer radius of 400 AU and are uniformly placed at 100 pc to allow for ease in distance scaling. One can see the effect of direct gas heating as the earlier type stars have strong flux and have greater spacing. For cooler stars the lines bunch together as the region where the gas and dust temperatures are decoupled is reduced. Regardless the mass dependence is clear.

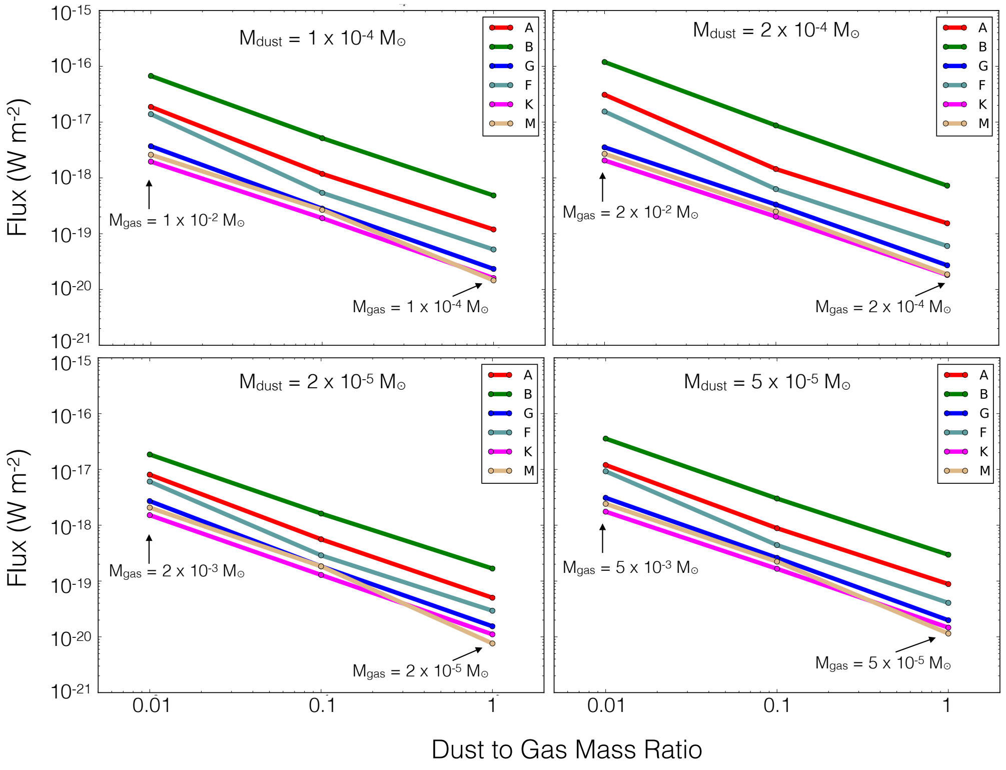

Figure 2 Plot of predicted HD J = 1-0 flux density for a range of models assuming different dust masses, dust-to-gas mass ratios (i.e. gas mass), and stellar spectral type.