Measuring Turbulence in a Protoplanetary Disk with CO

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Turbulence and Planet Formation
Turbulence is expected to be prevalent within protoplanetary disks, serving as a main driver for angular momentum transport and accretion through the disk (e.g. Turner et al. 2014). These random motions can also have an impact on planet formation. Large turbulent motions could increase the erosive collisions of planetesimals (Ida et al. 2008) and increase the relative velocities of sub-micron sized particles enough that they fragment rather than stick (Poppe et al. 2000, Gundlach et al. 2011). Low levels of turbulence allow small dust grains to settle to the midplane where they can aggregate into larger particles (Ciesla et al. 2007). Turbulence could counteract the inward motion of small planets associated with Type I migration (Laughlin et al. 2004). Turbulence and Planet Formation

Using molecular lines to constrain turbulence
Molecular emission lines trace the dynamics of the cold outer disk and can be used to search for turbulent motion. Recent ALMA CO measurements (~0.7\" resolution, 100-300m/s channel widths) of HD 163296 (~2.3 Msun, 122 pc away, ~3 Myr old) are able to spatially resolve the front and back side of the disk. The lack of CO emission between these layers is direct evidence of a cold midplane (Rosenfeld et al. 2013) and can be used to constrain thermal structure, a key degeneracy with turbulence. These studies provide tantalizing evidence for turbulence within the disk, and newer data, especially from ALMA, may allow for tighter constraints on the strength of the turbulence. Here we take advantage of science verification ALMA data of CO 3-2, CO 2-1, 13CO 2-1 and C18O 2-1 within HD 163296. For the first time we combine all four CO lines into a statistical robust measure of turbulence in HD 163296.

Results:

CO 3-2 constrains turbulence to <3% of the sound speed

(Top): CO 3-2 channel maps comparing the best fit model (black contours) with the data (colored contours). Contours are in units of 0.14Jy/beam. (Bottom): Channel maps derived from visibility residuals (red/black contours).

Using the disk models of Rosenfeld et al. (2013), along with an affine-invariant MCMC code (Foreman-Mackey et al. 2013) we seek to find the best fit model parameters (three describing the density structure, three describing the temperature structure plus turbulence and inclination) along with their uncertainties, and any degeneracies, while accounting for both statistical and systematic uncertainties using all four CO emission lines.

While simulations (e.g. Simon et al. 2015) predict \(v_{\text{turb}}=0.3-0.5c\) in the upper layers of the disk, we find that the CO 3-2 data (black solid line) are best fit by models with \(v_{\text{turb}}=0.3c\) (red-dotted line). Fitting the data with turbulence fixed at the spectral resolution (\(v_{\text{turb}}=0.1\text{km/s}=0.15c\)), while allowing the other model parameters to vary produces a significantly worse fit (blue-dashed line), confirming the low level of turbulence and our ability to push below the spectral resolution. The change in peak-to-trough ratio between the high/low turbulence models is similar to that predicted by Simon et al. 2015 based on simulated observations of numerical MRI models.

Taking advantage of the more robust constraint on disk structure from the simultaneous fitting of all four emission lines (left panels) we find a low level of turbulence (\(v_{\text{turb}}=0.16c\)), consistent with the CO 3-2 fit. Our limit on turbulence from CO 3-2 implies \(v_{\text{turb}}<1c\), suggesting that MRI is less efficient in the outer disk than previously thought. We measure weak turbulence despite the strong accretion rate onto the star (5e-7 M\(\odot\)/yr), suggesting that either the turbulence increases strongly toward the inner disk, or that angular momentum is removed by a process that does not drive strong turbulence.