Empirical Constraints on Turbulence in Protoplanetary Accretion Disks

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ABSTRACT

Turbulence is the most commonly invoked source of the viscosity that drives the transport of gas and dust through circumstellar disks, determining the amount and location of material available for planet formation. ALMA's high sensitivity will enable investigations of millimeter lines at much higher spectral resolutions than typically considered today, which provides access to information subtly encoded in line profiles like turbulence. As an example of this new direction, we present arcsecond-scale Submillimeter Array observations of the CO J=3-2 line from the disks around the young stars HD 163296 and TW Hya at 44 m/s resolution. These observations probe below the ~100 m/s turbulent linewidth inferred from lower-resolution observations, and allow us to place constraints on the linewidth in the disk atmospheres. We reproduce the observed CO(3-2) emission using two physical models of disk structure: (1) a power-law temperature distribution with a tapered density distribution following a simple functional form for an evolving accretion disk, and (2) the radiative transfer models developed by D'Alessio et al. that can reproduce the dust emission probed by the spectral energy distribution. Both types of models yield a low upper limit on the turbulent linewidth (Doppler b-parameter) in the TW Hya system (<40 m/s), and a tentative (3σ) detection of a ~300 m/s turbulent linewidth in the upper layers of the HD 163296 disk. These correspond to roughly ≤10% and 40% of the sound speed at size scales commensurate with the resolution of the data. The derived linewidths imply a turbulent viscosity coefficient, α, of order 0.01 and provide observational support for theoretical predictions of subsonic turbulence in protoplanetary accretion disks.

1. MEASURING TURBULENCE IN THE ATMOSPHERES OF TWO DISKS

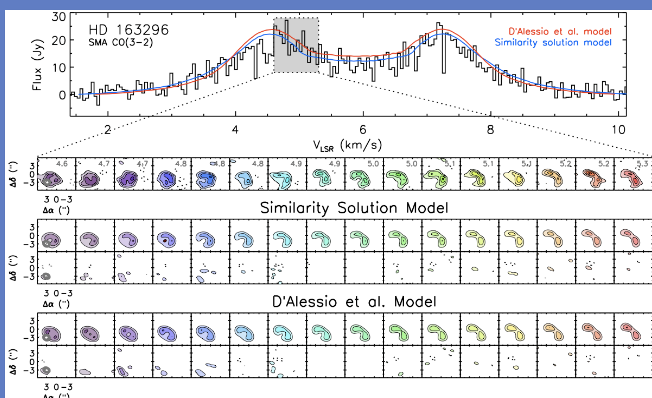

Fig. 1.— Comparison of CO(3-2) emission from HD 163296 between the data and best-fit models for a subset of the data. The top row of channel maps show the segment of the line indicated by the shaded gray box; the central row shows the corresponding channels of the best-fit similarity solution model and residuals; the bottom row shows the best-fit D'Alessio et al. model and residuals. Contours are [3,6,9,...] ×0.55 Jy/beam (the rms noise).

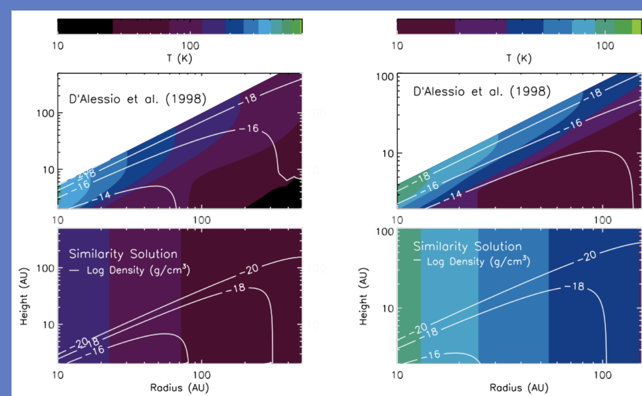

Fig. 2.— Comparison between the temperature and density structures of the similarity solution and D'Alessio et al. models for HD 163296 (left) and TW Hya (right). The bar across the top shows the temperature scale; white contours represent density (log total mass in g/cm^3). The abscissae of the plots are scaled to match the radial extent of the power-law disk model, although the similarity solution models will extend farther.

The HiRes mode of the SMA correlator is well-suited for measuring turbulence in protoplanetary disks, since it allows us to resolve the lines below the 100 m/s turbulent linewidth predicted from lower-resolution observations. Fig. 1 shows a subset of the HD 163296 channel maps; the full channel maps for TW Hya stretch across the bottom of the poster in Fig. 4. These are compared with the two classes of models shown in Fig. 2; despite their different treatment of temperature, both classes of models fit best with a subsonic turbulent linewidth of 300 m/s for HD 163296 and <40 m/s for TW Hya. Because of the high optical depth of the CO(3-2) line, this linewidthh is measured several scale heights above the disk midplane. This marks the first observational effort with sufficient spectral resolution to constrain turbulent linewidths in circumstellar disks.

2. MEASURING HOW TURBULENCE CHANGES WITH HEIGHT ABOVE THE MIDPLANE

CO(3-2) observations probe several scale heights up into the disk atmosphere, yet most of the mass of planet-forming material should have undergone settling towards the disk midplane. In order to understand how turbulence affects the growth of planetesimals, we must therefore use lower optical depth tracers to probe turbulence closer to the midplane. We have observed the CO(2-1) and ^{13}CO(2-1) lines in the compact configuration of the SMA using the HiRes correlator mode; extended observations are currently in the queue. By modeling simultaneously the three tracers, each with a different optical depth, we will be able to constrain the vertical profile of temperature and turbulence in the disk.

Fig. 3.— ^{13}CO(2-1) spectrum from our compact HiRes SMA observations of HD 163296. We will combine these with extended observations and ^{12}CO(2-1) to obtain a vertical profile of turbulent linewidth in the disk.

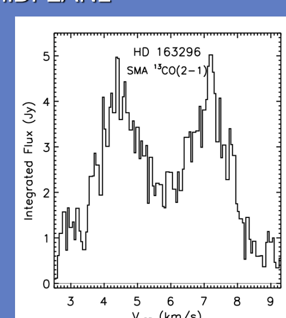

Fig. 4 (below).— Comparison of CO(3-2) emission from TW Hya between data (top), best-fit similarity solution (center), and residuals (bottom). Contours are [2,4,6,..]x0.9 Jy/beam (the rms noise).