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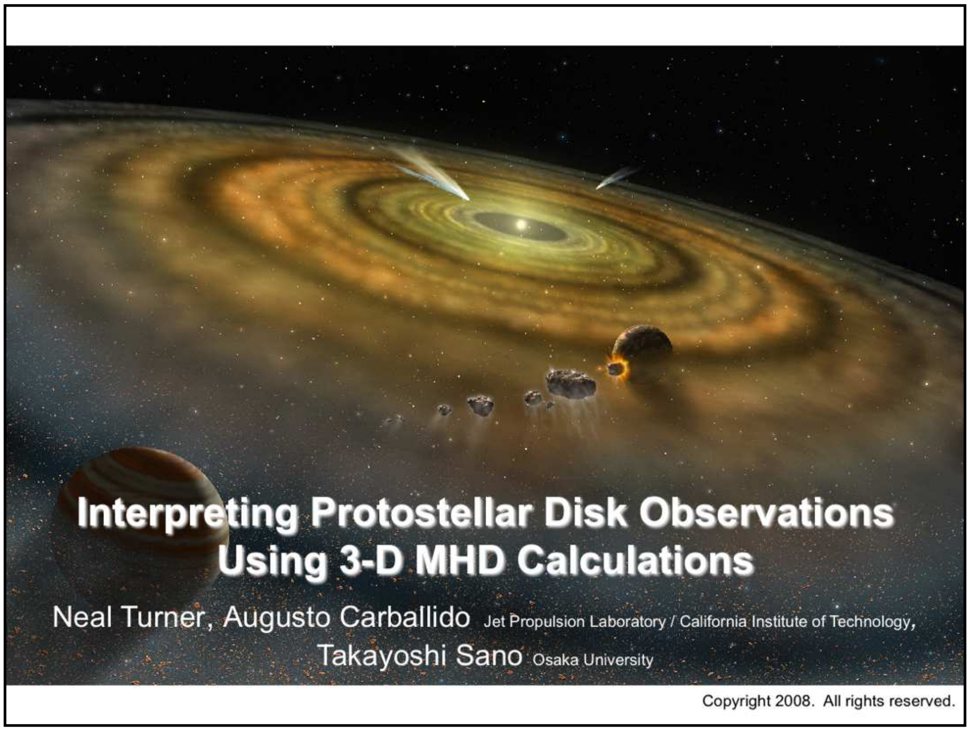

This talk deals with the flows driven by magnetic forces in the ionized parts of protostellar disks.

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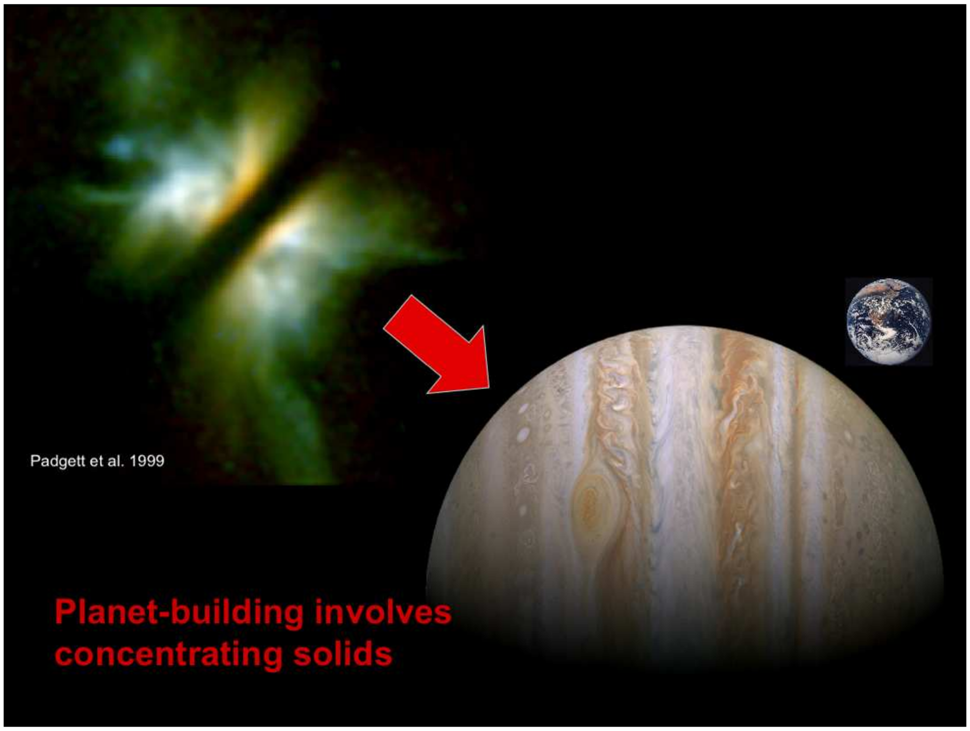

Concentration of the primordial solid material is a basic requirement for planet formation.

Processes involved might include settling, coagulation, radial drift, gravitational instability and preferential loss of the gas in a wind driven by magnetic forces or photoevaporation. Here we focus on settling, which likely operates during the earliest stages.

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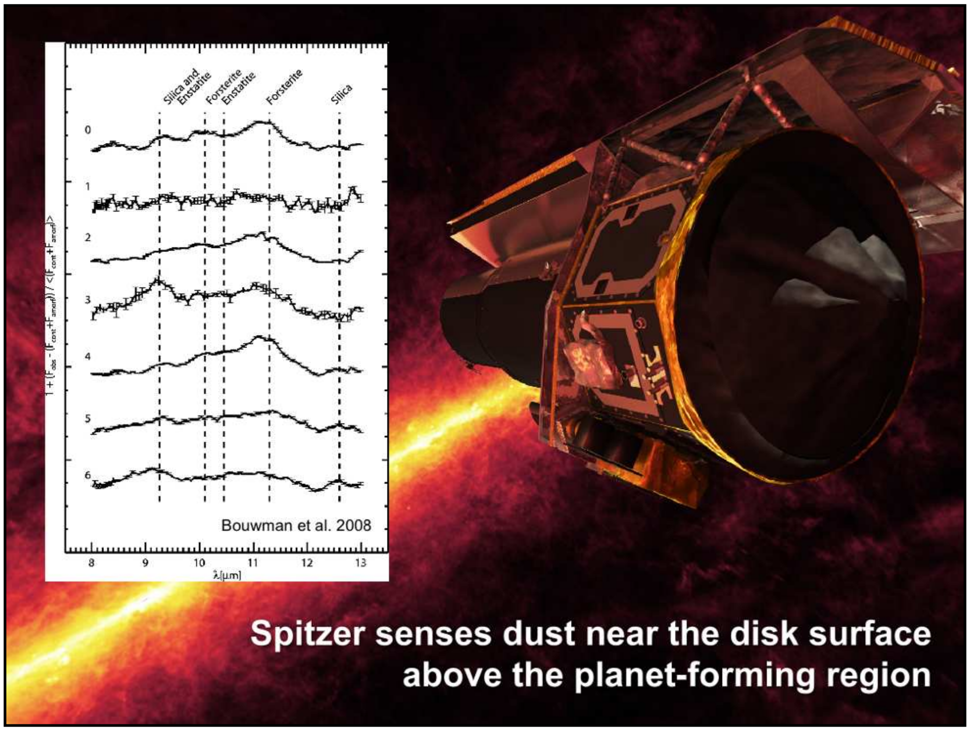

Spitzer measurements are sensitive to the abundance, size, composition and mineral structure of dust in the layers overlying the planet-forming region.

We are using first-principles models to investigate how gas flows within the disk might produce the observed dust signatures.

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1. Why the spread in accretion rates at a given stellar mass?

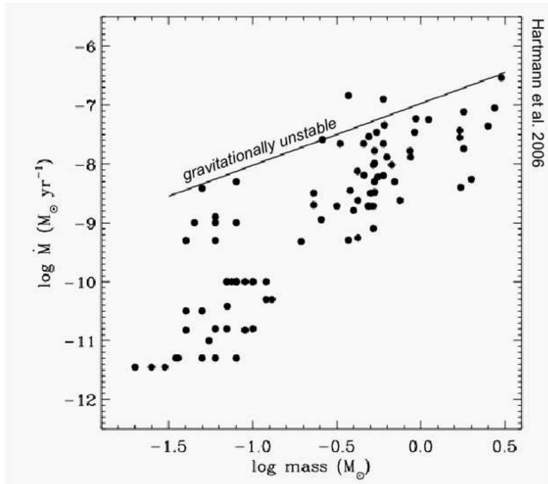
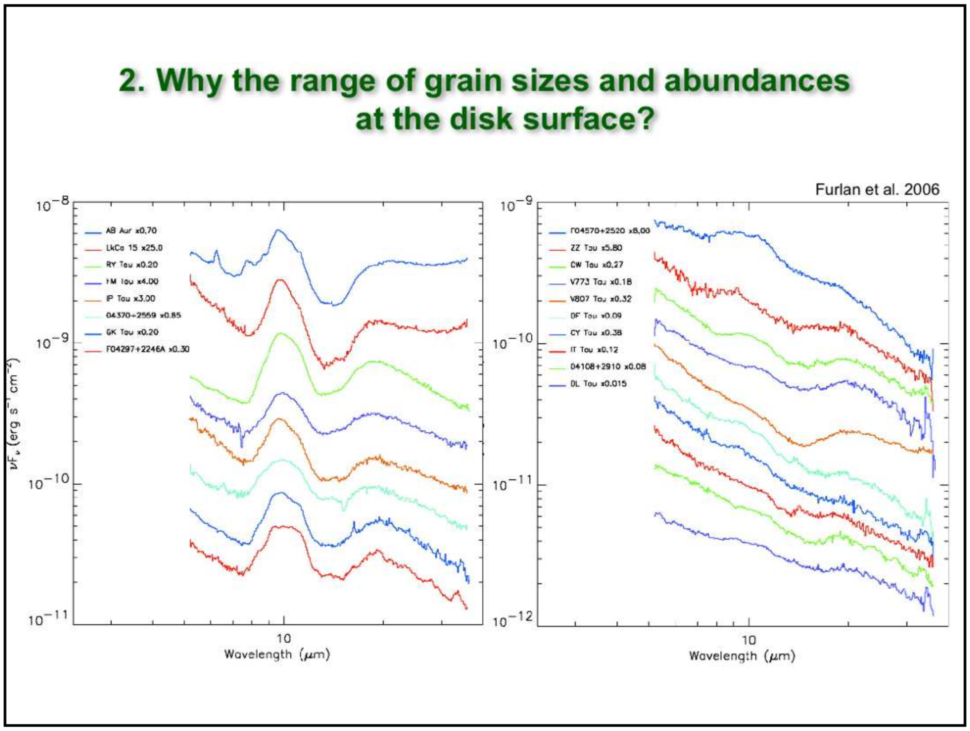


FIG. 1.—Relation of mass accretion rate and stellar mass, reproduced from Muzerolle et al. (2005), with the addition of a straight line indicating the relation $\dot{M} = 0.1 M_*/10^6$ yr. Above this line, sustained accretion for a typical age of 1 Myr would imply an initial disk mass likely to be gravitationally unstable (see text).

We want to understand: (1) The range in mass flow rate at a given stellar mass. Existing magnetic accretion models, with a fixed accreting column of 100 g/cm^2 set by the penetration depth of the ionizing cosmic rays, imply a fixed mass flow rate.



(2) The range in surface layer grain sizes and the diversity of features in the mid-infrared silicate bands.

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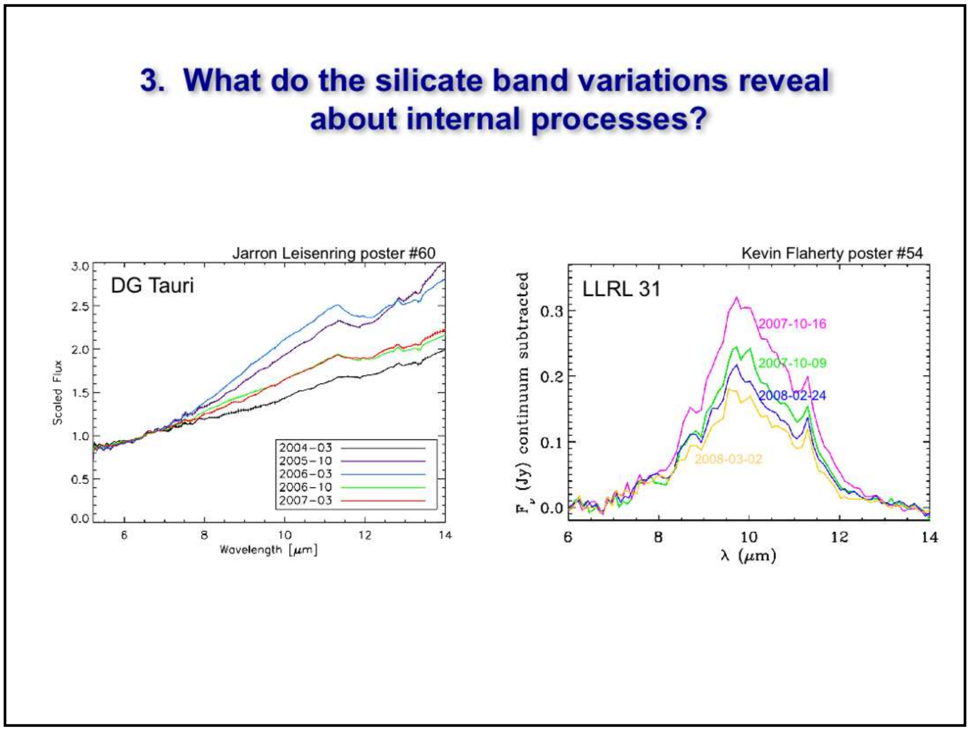

(3) Variability in the silicate features. Continuum variations are modeled in Kevin Flaherty's poster using shadows cast by disk warps and spiral waves.

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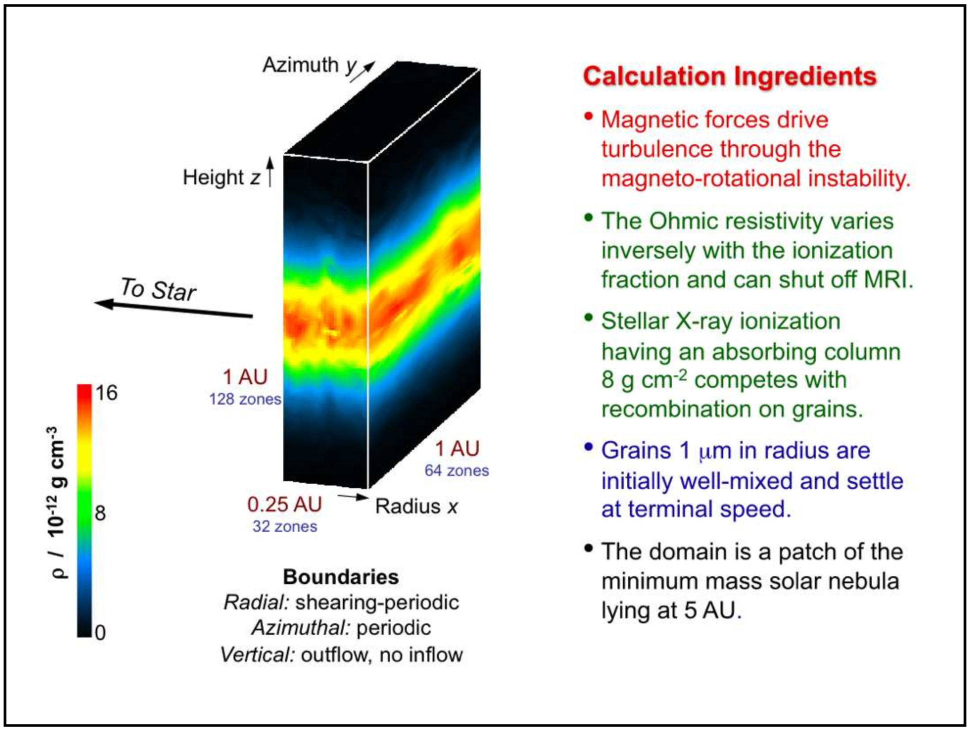
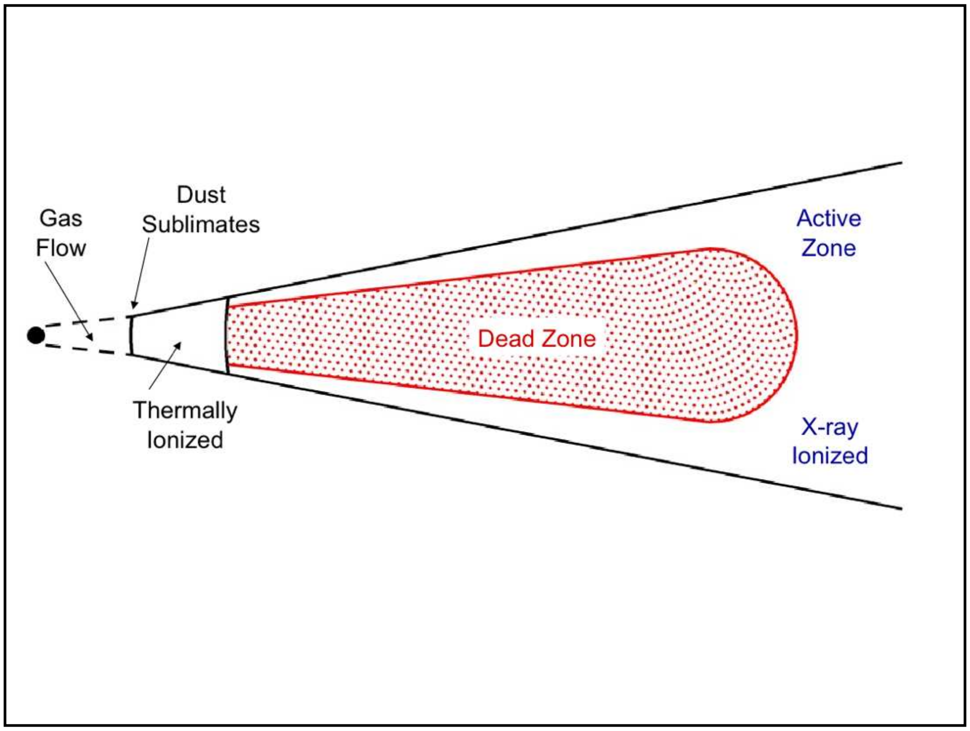


We examine settling & turbulent stirring with 3-D MHD calculations of a small disk patch, treating (1) turbulent stresses from magneto-rotational instability; (2) Ohmic resistivity, which can shut down turbulence; (3) ionization & recombination reactions, incl. stellar X-ray ionization & recombination on grains (the most important processes controlling the resistivity); and (4) settling of grains through gas.



The large absorbing column prevents X-rays from reaching the midplane. The resulting structure over most of the planet-forming region, including our patch at 5 AU, consists of turbulent surface layers sandwiching a “dead zone” where the gas is too weakly ionized for magneto-rotational turbulence.

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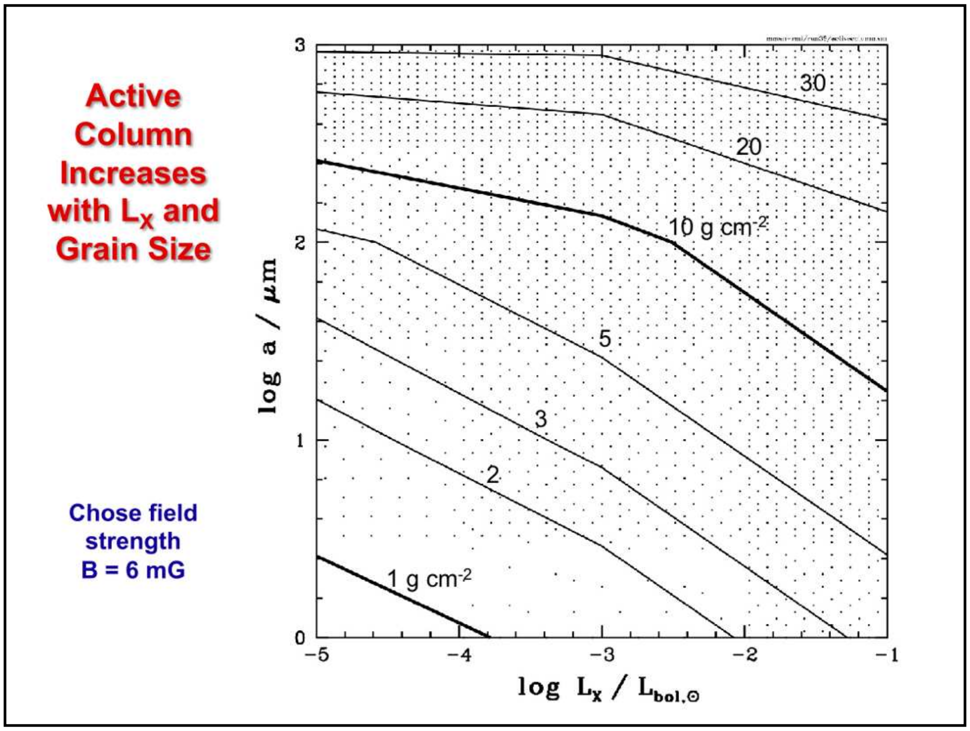

The magnetic field strength is chosen based on remanent magnetization measurements in meteorites that solidified in the asteroid belt during formation of the solar system. The resulting active or turbulent column increases with the grain size and the stellar X-ray luminosity, ranging over more than a factor 30. Adding a variety of magnetic field strengths easily yields active columns spanning a factor 100, matching the spread of accretion rates seen in T Tauri stars.

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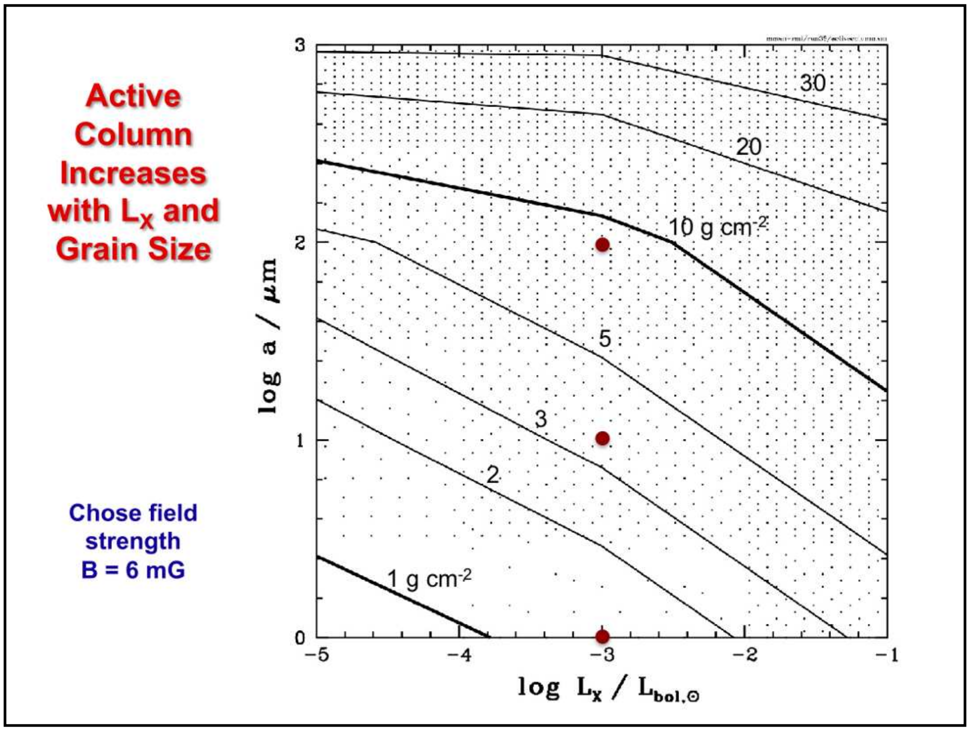

We measured the accretion stresses resulting from magneto-rotational turbulence in three MHD calculations with the parameters shown by the red dots.

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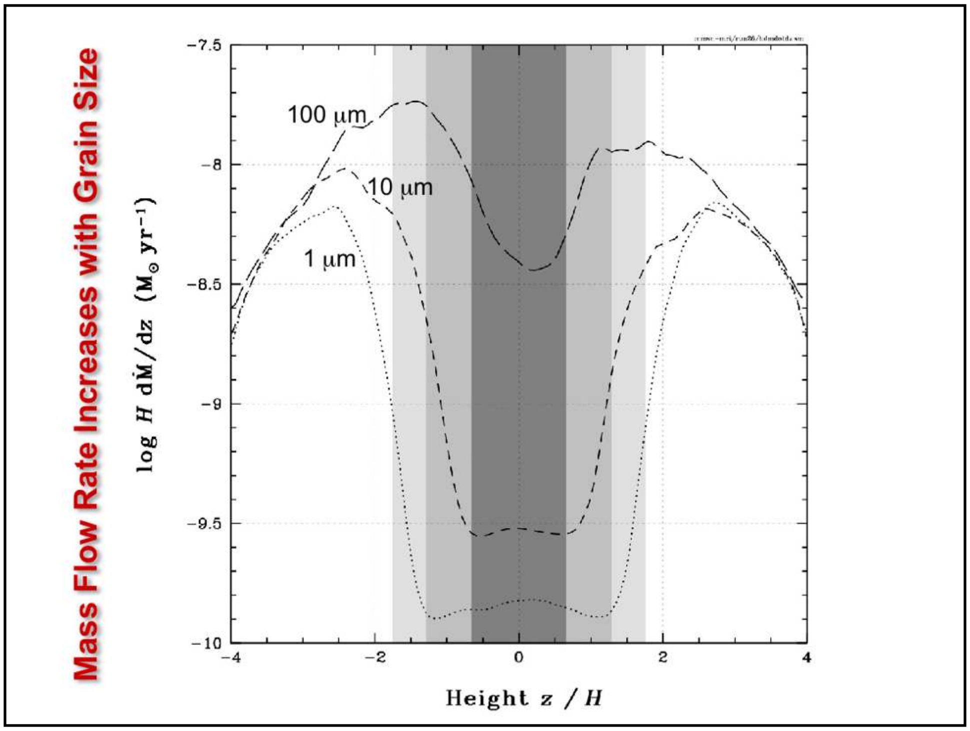

The mass flow rate increases with the grain size. Height-integrated accretion rates are 2, 3 and 7x10^-8 Solar masses per year. Grey bands show the dead zones in the three calculations.

For a contrary view where photoevaporation makes Mdot correlate inversely with L_X, see Jeremy Drake's poster #85.

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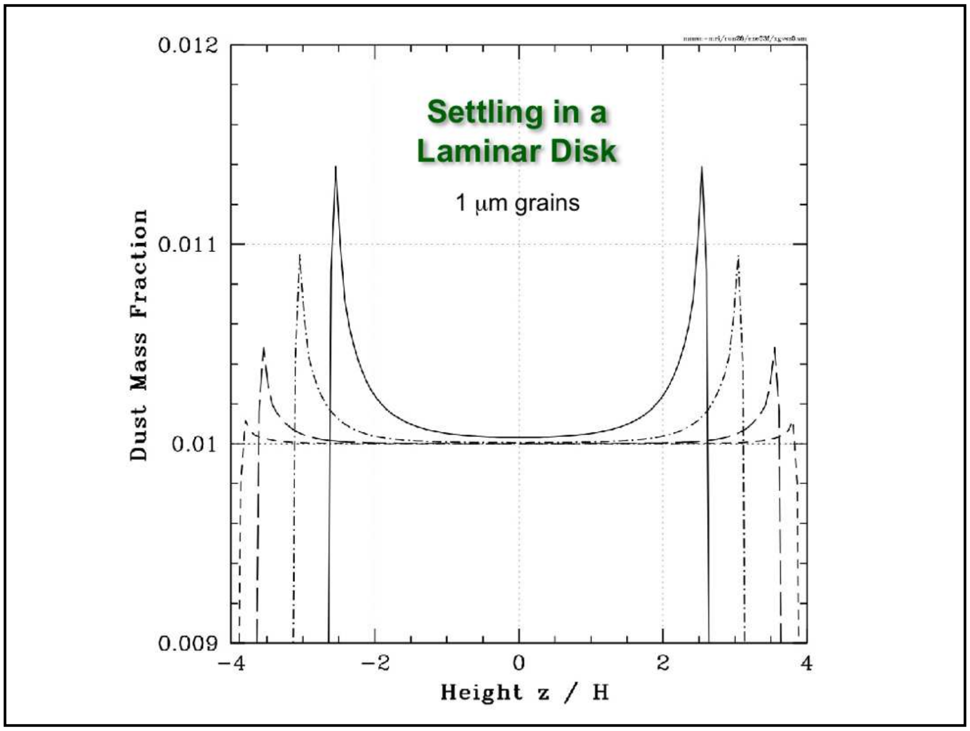
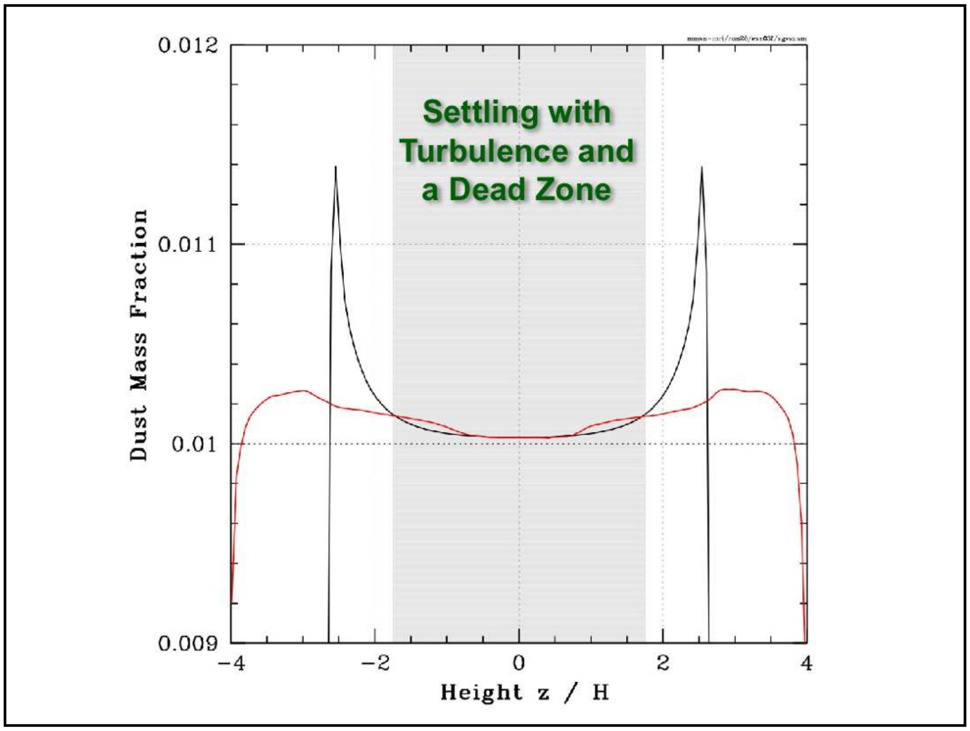
2. Why the range of grain sizes and abundances at the disk surface?

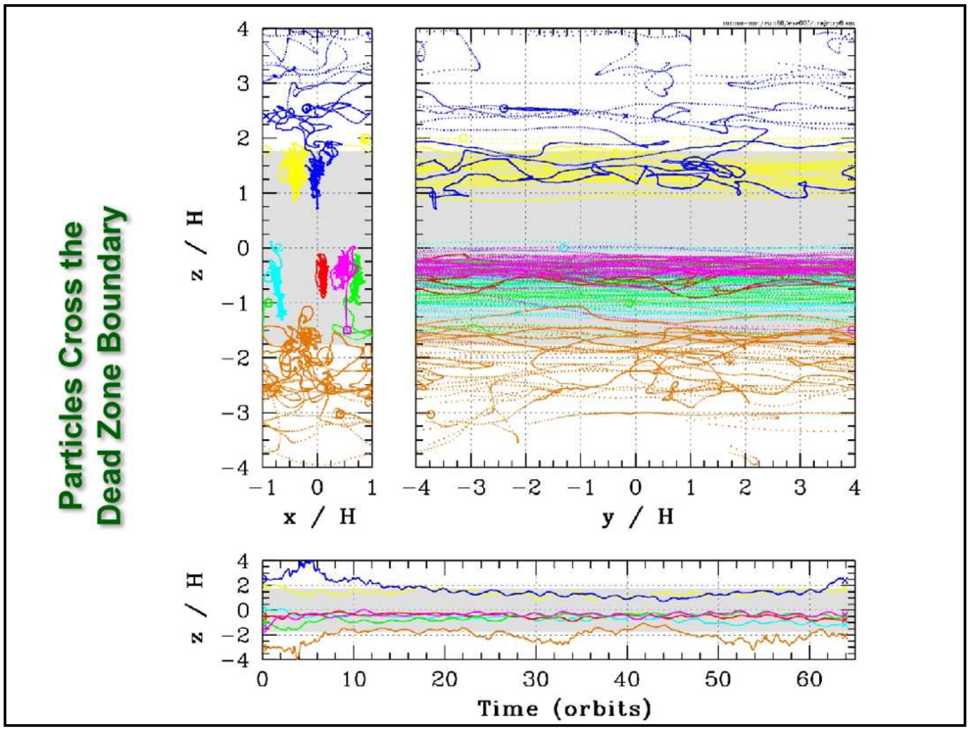


With no turbulence, initially well-mixed dust settles fastest in the outer layers, where the gravity is strong and the low density means weak gas drag.

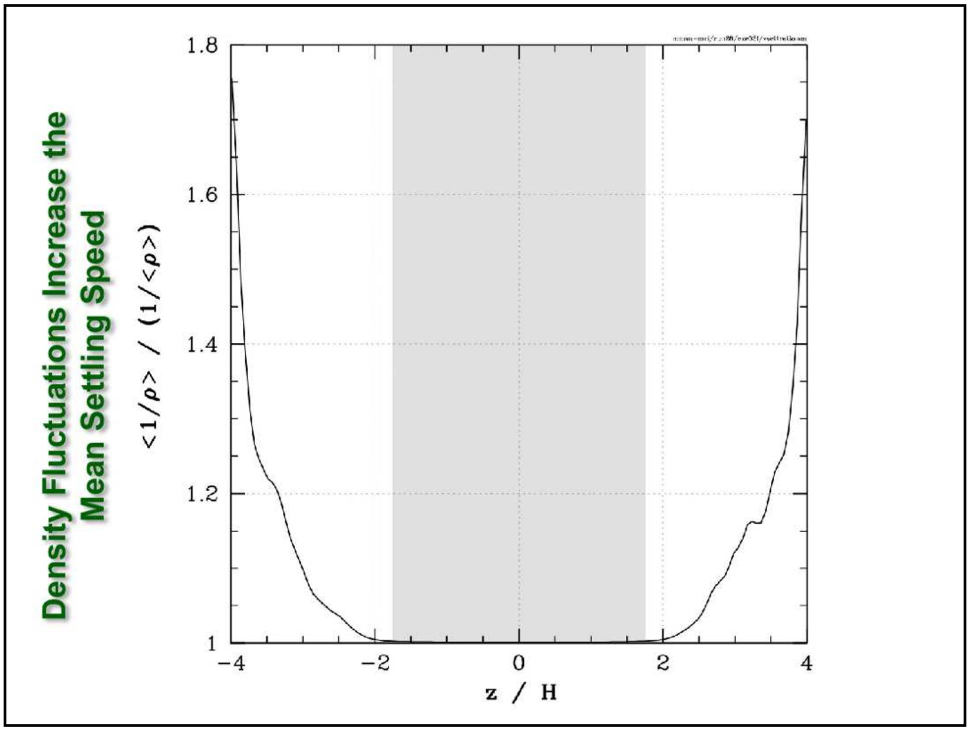
Settling is quick: the last snapshot is at just 60 orbits. Coagulation can make the settling faster still, as on Taku Takeuchi's poster #40, but here we assumed the particles do not stick to one another.



With turbulence (red curve), the more-settled outer material is mixed down to denser layers, leading to faster concentration of the solids there. This contradicts the usual wisdom that turbulence counteracts settling. In fact, what turbulence does is make the dust-to-gas mass ratio more uniform. When settling enhances the dust abundance in the outer layers, the turbulence spreads the enhancement into the interior.



We also tracked individual dust grains, finding that they are carried in and out of the dead zone when turbulent gas motions overshoot the dead zone boundary. The particle paths are viewed along the orbit (top left) and from the star (top right). Height vs. time is plotted below. Grey bands show the dead zone.



The settling speed is set by a balance between gravity and drag, so is inversely proportional to gas density.

Horizontal density fluctuations in the turbulence mean the average settling speed ~ <1/rho> is greater than the speed predicted from the mean density ~ 1/<rho> by 70% at 4H.

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3. What do the silicate band variations reveal about internal processes?

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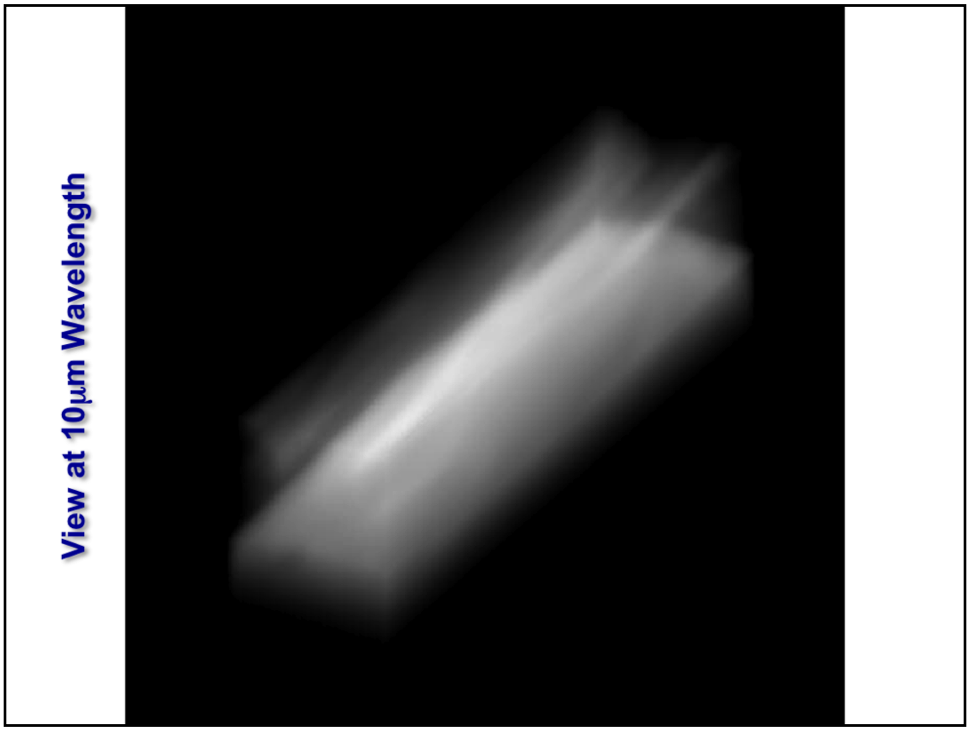
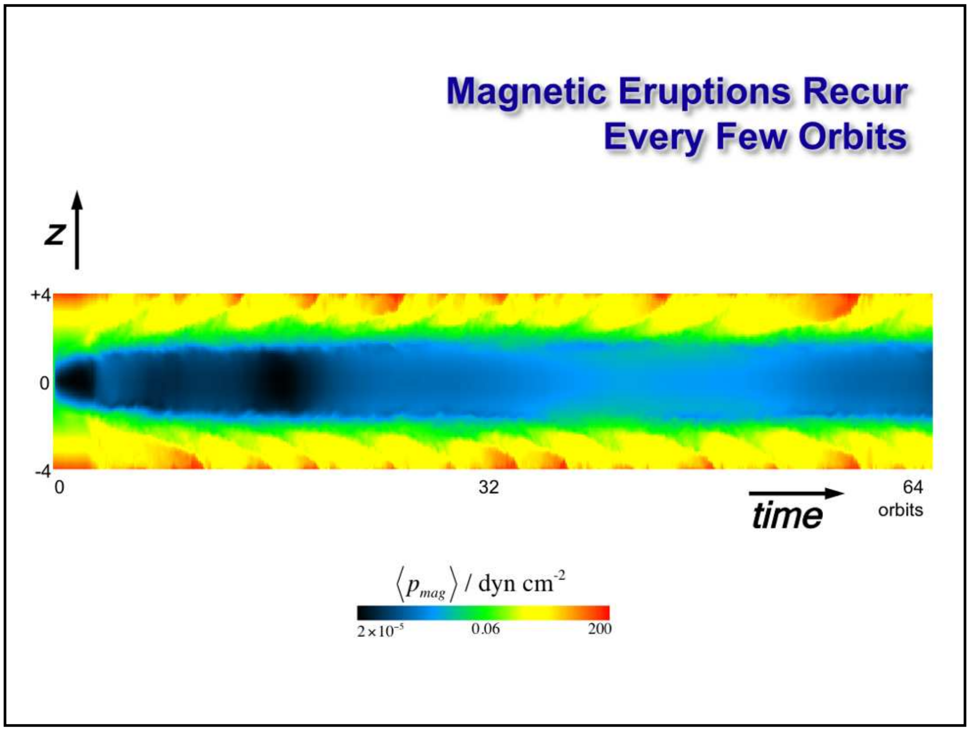


The movie shows that the turbulence in the active layers is variable. Every few orbits, the magnetic fields along the orbital direction grow strong through the shear, become buoyant and rise. Gas rising with the fields sweeps up dust, lifting the particles above the previous photosphere so they are heated by stellar irradiation and become bright in the 10-micron silicate band.



The eruptions of dusty gas recur episodically every few orbits along with the variations in the magnetic activity.

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Conclusions

- Can produce the observed spread in mass flow rate through differences in the grain sizes, stellar X-ray luminosity and magnetic field strength.
- Turbulence makes settling faster by (1) mixing dust-enriched gas into the interior and (2) driving gas density fluctuations. Expect the active layers to be near a balance between settling and stirring.
- The weak silicate bands of some T Tauri systems could result from grains sinking into the dead zone.
- Magnetic activity leads to silicate band variability over timescales 0.1 to 10 orbits.

Settling in the surface layers quickly reaches an equilibrium with turbulent stirring. The dust population can evolve further through either grain growth, or loss of particles to the dead zone, contributing to the diversity in the silicate features of T Tauri stars.

We suggest that time variations in the dust emission reflect magnetic activity related to that seen on the surface of the Sun.