

# Summary

Modeling the structure, chemistry and  
appearance of protoplanetary disks

Ringberg

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# Disk dissipation

- Coincidence NIR/submm disappearance of disks (Cathie Clarke).
  - Both measure dust.
  - Inner disk emptied by accretion
  - Outer disk by photo evaporation
  - Connection because photo evaporation at  $r_g$  stops feeding the inner disk.
- Questions
  - Does flushing the gas necessarily flush the dust in the outer regions?
  - Jupiter formation may require gas out to  $>10$ Myrs (David Hollenbach)
  - Can this gas be detected (David Hollenbach, Inga Kamp, Hideko Nomura)
- External photoevaporation (Sabine Richling)

# Chemical tracers for the gas

- Molecules require realistic disk models (Ewine van Dishoeck)
  - Simple model don't treat warm layer where almost all observable molecules exist.
  - Realistic models have
    - PDR at top
    - Warm layer just below
    - Cold midplane

## New gas diagnostics

- New diagnostics for the bulk disk gas are needed (Andres Carmona)
- H<sub>2</sub> is not really new, by maybe mature now
  - FUSE observations show the UV absorption lines in 17(?) sources (Claire Martin). Origin can be connected to
    - CS clouds (AB Aur)
    - hot gas above the disk chromosphere
    - 2 PDR models are needed to explain data
  - Models of H<sub>2</sub> emission (Hideko Nomura). Self-consistent 2D hydrostatic, with computed gas temperature
    - Strong UV radiation leads to hot gas with LTE lines, less UV drives some of the lines into non-LTE

## New gas diagnostics II

- $\text{H}_2\text{D}^+$  can be new tracer for midplane gas (Cecilia Ceccarelli)
  - Is it really the most abundant ion?
  - Dependence on Dust-to-gas ratio?
- S I in low-mass disks (David Hollenbach)
  - Should be very strong in Spitzer observations
  - But S can also be in the solids already (meteorites have S in FeS)
  - Too low densities will ionize to S II.
- PDR tracers for the top (see below)

# Mixing

- Seemed to get a lot of focus at this conference
- What mechanisms drive mixing?
- What effects does it have on Chemistry and Dust distribution?

# Mixing mechanisms

- Magneto-rotational instability works universally in weakly ionized gases (Steve Balbus).
  - It is NOT an alpha process, not a viscosity, but a stress tensor
    - Formally deriving an alpha describing the angular momentum transport does not mean one has the correct alpha describing turbulent mixing!
    - Growth time is fast, one orbit only
    - Mixing may be non-local (large scale radial streams)
    - It is all time dependent!
    - MHD modelers, please calculate the MRI mixing!
  - The dead zone may not be entirely dead
    - Will be emptied due to other effects or gravitational instability after mass loading?

# Mixing mechanisms (Klahr/Henning)

- Self gravity for massive disks
  - Adding B-field can reduce ang. mom. Transfer (Poster Fromang et al)
- Thermal convection
  - Only in active regions, and may not do the correct angular momentum transport???
- Baroclinic Instability (Hubert Klahr)
- Vertical Shear Instability (Rainer Arlt)
  - Is weak ( $\alpha \sim 10^{-5}$ ), requires vertical  $\Omega$  gradient
  - Can this work in the dead zone? Because the dead zone may be isothermal?
- Non-linear instabilities (Sandford Davis)
  - Do they really exist?
- Counter-intuitive flows
  - Midplane out, higher up in (alpha disk, Hans-Peter Gail)
  - Other way round (MHD, Steve Balvus)
  - Dust moves out in surface layer (Doug Lin)

# Mixing: Effect on Dust chemistry

- Global 1, 1+1, 2D models (Hans-Peter Gail)
  - Constant alpha disks lead to mixing timescales of  $10^4$  years at 1 AU to  $10^6$  years at 100AU. Mixing does not reach the outermost regions of the disk
  - Vertical mixing faster by factor  $(R/H)^2$
  - Carbon dust combustion products can be mixed out to regions where they would never be in LTE.
  - Crystalline dust can be mixed to 20% in Comet forming region.
- Models (poster Stefanie Walch)
  - Mixing can reach outer disk if the disk starts small and processes material fast which is then pushed outwards

## Mixing: Effect on Dust abundance

- Radial drift of dust can locally enhance dust abundances (Doug Lin)
  - Requires just the right diffusion
  - Can this help to make planets fast at specific locations?

## Mixing: Effect on chemistry

- Quench surface (review Ewine van Dishoeck) where  $t_{\text{chem}} = t_{\text{mix}}$ . Old models mostly accretion flows.
- Vertical mixing can be really important (Martin Ilgner)
  - LTE inside 1AU
  - Between 1 and 5 AU huge effects of vertical mixing on concentration of many species (CS ...)
  - Water comes of the grains due to vertical mixing

# Chemistry models

- Deuterium chemistry in the solar nebula: Clear predictions for cometary D/H ratios in various molecules (Andrew Markwick)
  - Surface chemistry not yet included
- Knowing the detailed UV field is important (Ted Bergin)
  - Ly $\alpha$  dominates UV in most stars.
  - Deep UV penetration may require X-ray  $\rightarrow$  electrons  $\rightarrow$  H<sub>2</sub> dissociation  $\rightarrow$  UV photon.
  - UV is very high in TW Hya and DM Tau, lower (?) in others.
  - Can we use smaller Networks? Bistability?

# PDRs

- PDRs provide well understood physics and lots of new diagnostics (Xander Tielens)
  - Small dust grains are essential for heating, H<sub>2</sub> pumping can help.
  - Measuring line and continuum emission allows to derive heating efficiency, i.e. dust properties.
- Lots of questions
  - Are PAH's like in the ISM?
    - Can be different from source to source
    - But abundance relative to dust seems to be the same as in ISM (Emilie Habart)
  - Can PAHs keep up the disk heating if the dust is settled?
  - Can small silicates contribute to heating?
  - Or X-rays?

## In thin air: PDRs above disk surfaces

- PDR models go to really extra-ordinary heights (Inga Kamp, Bastian Jonkheid):  $H/R=2$ 
  - Many assumptions become difficult
    - Disks are not thin anymore
    - Radiation does not come from top, but from the side and passes through the PDRs over inner disk
    - Densities are very low - will large PAHs start to settle?
    - How does mixing into these regions work?
  - Temperatures can be very high if the PAHs stay around, 2000K at 20AU (Hideko Nomura)
  - Dust and gas temperature couple at  $n \sim 10^6 \text{ cm}^{-3}$  (Inga Kamp)
  - Dust settling moves  $\tau=1$  surface down and changes temperature profile. Close to dust surface,  $T_{\text{gas}}$  is larger than in unsettled case (Bastian Jonkheid)

## Looking into the inner disks

- Interferometry at optical, NIR (Rafael Millan-Gabet, Jos Eisner)
  - Interferometry does not provide images, only visibilities, maybe phases.
  - Typical resolution 5 mas
  - Closure phase should be zero for non-flaring disks, but: scattering may be nonzero anyway.

## Disks seen with interferometry

(Millan-Gabet, Eisner)

- Observations need SED with stellar model
- Many disks require inner holes between 0.1 and 0.5 AU.
- Flaring disks with inner hole fit data OK, but not for early B stars, where flat disks are better.
- No significant closure phase detected yet for any disk.
- Inclinations are compatible with dynamic inclinations from mm data, but not with axis ratios.

## Mid-infrared interferometry

- 10  $\mu\text{m}$  interferometry resolves inner disk and shows strong dust processing (Roy van Boekel)
- How does the evolution go (observationally)
  - Amorphous/small  $\Rightarrow$  Crystalline/large
  - Crystalline/large  $\Rightarrow$  Amorphous/small

# Disks seen with (sub)mm interferometry (Geoff Blake, review)

- Current arrays:
  - Good: get  $V$  and  $\Phi$  , different resolutions from same data
  - Bad: Quantum noise is absolute image. When doubling array size, collecting area must go up a factor of 4.
  - Sensitivity of dust continuum and lines almost complementary.
  - Future: CARMA, then on to ALMA. ALMA does not need CLEAN procedure, which makes the errors a lot better understood. Full UV coverage in very short time.
- Clear evidence for cm grains in a number of sources (Antonella Natta)
- Submm lines can probe kinematics, for example measure radial motion in non-Keplerian disks (Michiel Hogerheijde, Poster Boogert & Blake)
- Plans in India to invest in submm Astronomy (R.S. Thampi).

# Gaps

- From SED in GM Aur (Kenneth Wood, also poster)
- Warping of the inner disk of AA Tau creates eclipses which can be used to analyze inner disk properties (Francois Menard)
- mm dust in the vicinity of a planet opens a gap earlier than the gas (Sijme-Jan Paardekooper)

# Dust growth: Observations

- Observations must be done careful, but can yield results.
  - 10 $\mu$ m Silicate feature can be used to measure dust growth, but only to  $\sim 2\mu$ m.
    - T Tau and Herbig star survey compatible with other data: Large grains go together with crystallinity (Jaqueline Kessler)
  - MIDI data shows that in the inner disks dust is more processed than in the outer disks (Roy van Boekel).
  - mm data clearly shows grains have grown to  $\sim$ cm (Antonella Natta, Mario van den Ancker)
  - Butterfly nebula requires larger grains in the disk than in the envelope, but details are very difficult to derive (Sebastian Wolf)
  - Gray eclipsing of star can also be total eclipsing in combination with scattered light (Francois Menard). The MRN can also work.

# Dust growth: Theory/Experiment

- Fluffy grains are really porous/fractal ... (Dominik)
- Electrostatic charging of dust grains accelerate coagulation (Gregor Morfill)
  - But gas must not be charged at all.
  - Single, like charges enough?
- Growth of large bodies makes significant problems
  - Gravitational instability can only work under very special circumstances
  - Restructuring can absorb energy (Carsten Dominik)
  - Aerodynamic support of growth by collecting collision debris (Gerhard Wurm)
- Shocks as source for processing of dust (Taishi Nakamoto)
  - So how important is mixing really?

# Is coagulation fast or slow?

- Coagulation is slow and sluggish
  - Fractal aggregates (Dominik)
  - Aerodynamics required to allow net growth in the m range (Wurm)
  - Need electrostatic forces (Morfill)
- Coagulation cannot be fast and complete (Dullemond and Dominik)
  - Disk models require small grain for 10 Myrs
  - 1 $\mu$ m grains remain visible at surface even though they should settle and grow
  - Shattering is needed to keep small grains
  - PAHs remain in upper disk, in ISM ratio (Habart)

## Radiative transfer tools

- Phoenix: Stellar atmosphere code applied to disk surface (Jean-Francois Gonzales)
- 2D Monte Carlo (Wood, Dullemond)
- 2D Variable Eddington (Nomura, Dullemond)
- Line transfer Monte Carlo (Hogerheijde)
- PDR codes (Kamp, van Dishoeck, Jonkheid, Tielens, Hollenbach)

# Global disk models

- Model for AB Aur including continuum, chemical model and line transfer reproduces many observations (Katharina Schreier)
  - “inverse P-Cygni profiles” at 600 AU.
- 2D RT modelling of Class I sources with disk/envelope shows correlation  $M_{\text{env}}/M_{\text{disk}}$  with  $M_{\text{tot}}$ . Large total mass implies large disk mass (Takeshi Nakazato)
  - Trend  $M_{\text{acc}} - M_*$  confirmed for  $\rho$  Oph and BD (Natta)
- Dust settling can produce strong variations in disk shapes (Kees Dullemond).
- Self-shadowed disks can explain group II sources with low small-grain masses. Mineralogy and grain size important for group Ib sources (Joke Meijer).
- 3D SPH with dust (Poster Barriere et al).

# The Planet connection

- Could a planet explain the fast-rise FU Orionis outbursts (Giuseppe Lodato)
- Type I migration can be slowed down or reversed by magnetic fields (Caroline Terquem)
- Hot spots by small planets, gaps and small SED modifications for large planets (Geoff Bryden). But not every SED wiggle is a gap.
- AGB phase mass loss moves planets away from star, helping detectability (Hans Zinnecker)

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