The properties of the gas around Beta Pictoris
Gas evolution in disks

Star formation

**Gas Mass**

- $10 - 100 \, M_{\text{Jupiter}}$
- Few $M_{\text{Lunar}}$ (dust)

**Total Mass**

- $10 - 100 \, M_{\text{Jupiter}}$
- ?

**Time (Myr)**

- 1
- 5
- 10
- $\sim 1 \, \text{Gyr}$

**Observation**

- Primordial disk
- Transitional disk
- Debris disk

- T Tauri & Herbig Ae/Be stars
- Main sequence stars

**Planetary system**
The early clues: shell stars

- “Grab bag” of stars w/ narrow absorption lines
- Beta Pic classed as shell star (Slettebak 1975, 1982)
- Beta Pic circumstellar gas discovered before the dust! (Aumann 1984, Smith & Terrile 1984)
Gas absorption toward Beta Pic

- Optical / UV absorption spectroscopy
- Lines too strong to be interstellar (e.g. Vidal-Madjar et al. 1986)
- Many lines & species not seen in local ISM (e.g. Lagrange et al. 1998)

TALK: Vidal-Madjar
The absorption components

Narrow unvarying features
at $\nu = \nu_{\star}$: stable gas

Variable shifted features:

FEBs = star-grazing planetesimals
Star-grazing planetesimals

- Usually redshifted, 10s to 100s of km/s
- Variable on timescales as short as hours
- Highly ionized species: hot, dense gas
- Variable gas is clumpy

Bouret et al. (2002)

e.g. Lagrange et al. (1986), Ferlet et al. (1987), Lagrange et al. (1988), Beust et al. (1990), Vidal-Madjar et al. (1994)

TALKS: Beust, Kiefer
Molecular gas

- Undetectable CO emission (e.g. Zuckerman et al. 1995) ... until ALMA

CO absorption (e.g. Deleuil et al. 1993) ... but no H$_2$

Roberge et al. (2000)

Lecavelier des Etangs et al. (2001)

Primordial gas gone
Summary: the nature of the gas

- Stable gas is not interstellar
  - Too strong, wrong velocity, lines from excited levels
- Relatively low gas abundance, primordial gas gone
  - No sub-mm CO emission, no H$_2$
- Recently produced secondary gas!
  - No shielding of stable gas from UV radiation
  - Species with short ionization / dissociation lifetimes
- Possible production processes: comet evaporation, grain-grain collisions, photodesorption
Gas dynamics problem

- Radiation pressure should blow away much stable gas
- Need braking gas
- Hydrogen torus close to star? (Lagrange et al. 1998)
- Not enough H or H$_2$, unless all stable gas is close to the star
  (Freudling et al. 1995, Lecavelier des Etangs et al. 2001)
Rotating gas disk

- Spatially resolved optical spectra of resonantly scattered atomic emission (e.g. Olofsson et al. 2001)
- Gas in Keplerian rotation out to 100s of AU
- Need a LOT more braking gas

TALK: Brandeker
Dynamics problem solved: carbon

- Coulomb breaking: ions couple into single fluid (Fernandez, Brandeker, & Wu 2006)
- If $C > 10 \times$ solar, gas will self-break

![Beta Pic Gas Abundances Relative to Solar](image)

Roberge et al. (2006)

$C/Fe = 16 \times$ solar
Elemental abundance problem

- Depletion of elements feeling strong radiation pressure could cause carbon overabundance
- But oxygen should also be overabundant

![Beta Pic Gas Abundances Relative to Solar](image)

**Nope.**

C/O = 18 x solar
Far-IR oxygen & carbon emission

- C/Fe ~ 400 x solar
- C/O ~ solar
- Rich in carbon AND oxygen
- Caused by differential depletion?
- Overproduction of C and O slightly favored

(Xie, Brandeker, & Wu 2013)
The ALMA era: asymmetric CO enhancement

Dent et al. (2014)

TALK: Dent
CO clumps

De-projected views from above the Beta Pic disk

Dent et al. (2014)

Comet swarms in mean-motion resonance with planet

Recent collision of Mars-mass icy bodies

Plus tenuous CO torus at 50 – 160 AU

TALKS: Wyatt, Jackson
Absorption measurements said not enough CO to be sole source of carbon

- C I ionization time and CO dissociation time both \( \sim 120 \) years. Expect equal amounts in equilibrium
- In the line-of-sight, CO is \( \sim 2\% \) of C I (Roberge et al. 2000)
- Postulated additional source of carbon

Now know most CO is not in the line-of-sight

Enough to supply whole disk? Upcoming ALMA C I map will tell
Summary

Volatile-rich atomic gas

CO torus

CO clump

Comets
Questions

- What do the gas abundances mean?
  - Revisit UV spectroscopy of O and Si in particular

- What is causing the CO clumps?
  - Somebody look for a planet at ~ 60 AU!

- Is Beta Pic representative of debris gas?
  - Roughly 8 debris disks with gas, plus similar number of candidates
  - Analysis of 49 Ceti far-UV spectra and ALMA CO map in progress (Roberge et al.; Hughes et al.)