Formation and dynamical history of the β Pictoris system

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Main dynamical indicators

The planet beta Pic-b
(its orbit and spectrum)

FEBs (velocity distribution)

Warp in outer disk

Clump in outer disk
Descendant of protoplanetary disk

System formed in protoplanetary disk akin to Herbig Ae stars

PPDs last a few Myr then disperse rapidly... somehow

β Pic has relatively bright disk, possibly because it is young
Formation mechanism for β Pic-b

Can be formed in core accretion models implying a core of \( \sim 200 \text{M}_{\text{earth}} \) (Bonnefoy et al. 2013)

Hard to form in situ by gravitational instability (Rameau et al. 2013)

- But could have migrated, and model assumptions are somewhat flexible
- Implications for other planets in system (e.g., why just one core?)
- Regardless, formed in PPD

See Mickael Bonnefoy’s talk
Two temperature $\beta$ Pic debris disk

Spectrum shows thermal emission from dust at a range of wavelengths.

Reasonable fit with two (modified) black bodies at 484 and 107K suggesting two spatially distinct regions.
Inner planetesimal belts?

Inner component poorly constrained as small and next to bright star, but fit to mid-IR spectrum inferred multiple belts (Okamoto et al. 2004)

Makes sense dynamically that gaps in distribution are caused by planets
Dynamical lifetimes in planetary systems

Overlapping resonances near planets quickly clear gaps (Wisdom 1980)
\[ \frac{a}{a_{\text{pl}}} = 1 \pm 1.3 \left( \frac{M_{\text{pl}}}{M_\star} \right)^{2/7} \]

Chaotic region extends further for multi-planet systems, but these regions are cleared on 10 Myr timescales

Asteroid and Kuiper belts only locations in Solar System stable for >4.5 Gyr (Lecar et al. 2001); perhaps 6 au and >60 au regions are analogous for β Pic?
Falling Evaporating Bodies

Transient absorption features explained by interior resonances (4:1 or 3:1) with \( \beta \) Pic-b where eccentricities can be driven to >0.9 (Beust & Morbidelli 1996, 2000)

Dynamics explains predominantly red-shifted absorption features (for \( e_b=0.05-0.1 \)), but do blue-shifted features imply interior planets?

Also, what is the mechanism feeding the resonance – collisions in the belt, ongoing migration (Thebault & Beust 2001)?

See Herve Beust’s talk
Where are planetesimals in outer disk?

ALMA mapped 850\(\mu\)m emission from mm-sized grains at \(~0.5^{\prime}\) (~10AU) resolution down to star (Dent et al. 2014)

Fit to surface brightness profile shows planetesimals in broad belt 60-130au (Dent et al. 2014) as expected from fit to scattered light (Augereau et al. 2001)
How are the planetesimals stirred?

Initially km-sized planetesimals grow to Pluto-size, stir their immediate vicinity igniting a collisional cascade and producing dust (Kenyon & Bromley 2004; 2010)

Resulting surface brightness profile peaks where Plutos recently formed (Kennedy & Wyatt 2010)

If so, inner regions are collisionally depleted and Plutos at 60-130au
If $\beta$ Pic-b is eccentric, stirring is inevitable.

Secular perturbations cause eccentricity pumping and differential precession, ultimately leading to orbit crossing (Mustill & Wyatt 2009).

Timescale is

$$ t_{\text{cross}} \sim a^{9/2} a_{pl}^{-3} M_{pl}^{-1} e_{pl}^{-1} $$

12 Myr at 75 au for $\beta$ Pic-b.
Warp in outer disk

Same perturbations also cause a warp if β Pic-b is misaligned with disk mid-plane (Mouillet et al. 1997; Augereau et al. 2001)

The disk is warped from 50-100AU

Orbit of β Pic-b is plausibly aligned with the warp rather than the outer disk mid-plane (Lagrange et al. 2012)
Is orbit of β Pic-b aligned with disk?

Orientation of the line of nodes affects both magnitude of warp (Mouillet et al. 1997) and shape particularly in inner disk (Matthews et al. 2014; Apai et al. submitted).

Note that outer disk has some vertical extent – it has already been stirred?
Do inner planets help?

Secular perturbations acting on outer disk are sum of those from all planets in system so alignment of outer disk with $\beta$ Pic-b is not inevitable (Dawson et al. 2011)

But a planet that perturbs the outer disk would also perturb $\beta$ Pic-b

A multiple planet system would also have unstable secular resonances that could deplete disk
Origin of inner hole?

Outer planetesimals are icy (Dent et al. 2014) – is inner edge at CO snow-line?

Or is it related to the mechanism causing the inner hole in transition disks (van der Marel et al. 2013; Pinilla et al. 2014)?

Or are the inner regions collisionally depleted (Kennedy & Wyatt 2010)?

Or are they cleared by planets?

E.g., at 30au for TWHya Qi et al. (2013)
Brightness asymmetry from clump

850μm emission and CO toward β Pic show asymmetry at ~50AU projected separation, coincident with a similar asymmetry seen in mid-IR (and with warp)

Originates in a clump at 80au projected separation (from CO velocity information)
Giant impact at 85AU onto Mars-sized parent, debris escapes at ~4km/s (Jackson et al. 2014)

Stays as clump <1 orbit (580yr), but asymmetric for ~1000 orbits (0.6Myr), as orbits go through the collision point

Collision rate enhanced at bottleneck where most CO and small dust produced
Problem: clump should be stationary

In the giant impact model the clump remains fixed at the point at which the first impact occurred.

Reimaging at 11.7μm after 7 yrs shows a 2AU (3.6σ) move to right (Li et al. 2012)
Resonance sweeping model

The outward migration of a Saturn-mass planet sweeps comets into its resonances

Wyatt (2003)
Geometry of resonance

3:2 Resonance

A comet in 3:2 resonance orbits the star twice for every three times that the planet orbits the star.

Geometry causes planetesimals to get periodic kicks from the planet’s gravity, which can cause some to become trapped.

Also means planetesimals spend most time at certain longitudes relative to the planet.
### Explains wavelength dependent disk structure

<table>
<thead>
<tr>
<th>Sub-mm continuum (planetesimals)</th>
<th>Mid-IR (small but bound dust)</th>
<th>Scattered light and short mid-IR (small unbound dust)</th>
<th>CO (short-lived gas)</th>
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<tr>
<td><strong>β Pic observed</strong></td>
<td><img src="image" alt="850µm" /></td>
<td><img src="image" alt="25µm" /></td>
<td><img src="image" alt="CO" /></td>
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<tr>
<td>Face-on resonance sweeping model (Wyatt 2006)</td>
<td><img src="image" alt="12µm" /></td>
<td><img src="image" alt="R" /></td>
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Constraints on $\beta$ Pic-c planet

Requires migration rates of 
$\Delta a \sim 15\text{AU}$
$\Delta t < 12\text{Myr}$
$a \sim 80\text{AU}$
$M_* = 1.75M_{\odot}$

Planet mass ($M_{\text{earth}}/M_{\odot}$)

- Limited parameter space; $M_{pl} > 35M_{\text{earth}}$
- Migration from planetesimal scattering or interaction with gas?
- But this model is not without problems

Less angular momentum than $\beta$Pic-b

Trapping into 2:1, which is also asymmetric but none in 5:3
Conclusions

- Overall: Most dynamics dominated by β Pic-b, but more precise orbit required
- Inner (<10au) planets poorly constrained, but very likely inner planetesimal belt
- Origin of 10-60au clearing unknown, but outer clump possibly explained by outward migration of Saturn-mass planet
- >60au filled with icy planetesimals and possibly embryos, since unlikely to be stirred by β Pic-b alone