Generating Vortices with Slowly-growing Gas Giant Planets

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van der Marel, N., et al. 2013
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Why so asymmetric?

ALMA Observations

Hydrodynamic Simulation

Jupiter-mass Planet

Oph IRS 48 (Dust)

van der Marel, N., et al. 2013

SR 21 (Dust)


Higher Density

Gas

Gap

This resemblance is well-known; e.g. (Li, H., et al. 2005; Zhu, Z. + Stone, J. 2014).
Why so asymmetric?

ALMA Observations
Hydrodynamic Simulation

Oph IRS 48 (Dust)
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Jupiter-mass Planet

Higher Density

This resemblance is well-known; e.g. (Li, H., et al. 2005; Zhu, Z. + Stone, J. 2014).

Dust
Why so asymmetric?

Oph IRS 48 (Dust)  
van der Marel, N., et al. 2013

SR 21 (Dust)  
~35 AU

Jupiter-mass Planet

Higher Intensity
This resemblance is well-known; e.g. (Li, H., et al. 2005; Zhu, Z. + Stone, J. 2014).
How can gap-opening planets create vortices?

To simulate this with FARGO (hydrodynamic code):
(1) Start with a gas disk with this radial density profile.
(2) Then, add a giant planet at $r = 1$ and run the simulation.

Sharp density peaks can make disks \textbf{unstable} (to the Rossby Wave Instability)
Vortex Evolution (with \textit{Instant} Planet Growth)

Notice:

(1) \textbf{Extent}: The vortex spans 120 degrees near the beginning.

(2) \textbf{Density}: It reaches an over-density of more than twice the initial density.

(3) \textbf{Lifetime}: It lasts for \(~8000\) orbits, making it observable.

\[
M_p = 1 \, M_{\text{Jup}} \quad \alpha_{\text{disk}} = 3 \times 10^{-5}
\]

\[
t = 0 \text{ orbits } \left[ m_p(t) = 0.00 \, M_{\text{Jup}} \right]
\]

Vortex Evolution (with *Instant* Planet Growth)

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How fast do giant planets grow?

Core Accretion Model for Giant Planet Formation:
Runaway Gas Accretion Phase

$M_{core} \approx 10 \, M_{\oplus}$

$M_{atmosphere} \approx 10 \, M_{\oplus}$

$M_{core} \approx 10 \, M_{\oplus}$

$M_{atmosphere} \approx 300 \, M_{\oplus}$
How fast do giant planets grow?

The runaway gas accretion phase can last for thousands of orbits.

Growth Times

\[ T_{\text{growth}} \approx 3000 \text{ orbits} \]
\[ T_{\text{growth}} \approx 20000 \text{ orbits} \]

Growth Models for Jupiter’s Runaway Gas Accretion Phase

Adapted from Lissauer et al. 2009

The runaway gas accretion phase can last for thousands of orbits.
Vortex Evolution (with *Slower* Planet Growth)

**Notice:**

1. **Extent:** The vortex spans about 240 degrees.
2. **Density:** It never reaches double the initial density.
3. **Lifetime:** It lasts for only $\sim 1500$ orbits. Then, it forms a ring.

Early Vortex Evolution

...with Instant Growth:

1. Planet grows to full size.
2. Disk becomes unstable.
3. A strong vortex forms.
4. Vortex smooths gap edge.

...with Slower Growth:

1. Disk becomes unstable.
2. A weak vortex forms.
3. Vortex smooths gap edge.
4. Planet grows to full size.
Vortex Extents with Slower Planet Growth

Concentrated (< 120°)
180 degrees

Vortex Extents with Slower Planet Growth

Vortex Extents with Slower Planet Growth

Concentrated (< 120°)
180 degrees
Elongated (> 240°)

Vortex Extents with Slower Planet Growth

Vortex Extents with Slower Planet Growth

Planets must grow to Jupiter size in <200 orbits to trigger a concentrated vortex.

Vortex Extents with Slower Planet Growth

Planets must grow to Jupiter size in <200 orbits to trigger a concentrated vortex.

Typical Jupiter analogs do not trigger vortices!

(e.g. Lissauer et al. 2009)

Dust Trapping in Vortices?

$M_p = 1 \, M_{\text{Jup}}$

$T_{\text{growth}} = 10 \text{ orbits}$
(Concentrated Vortex)

$\alpha_{\text{disk}} = 3 \times 10^{-5}$


Do elongated vortices trap dust the same way?

\[ M_p = 1 \, M_{\text{Jup}} \]

\[ T_{\text{growth}} = 1000 \, \text{orbits} \]  
(Elongated Vortex)

\[ \alpha_{\text{disk}} = 3 \times 10^{-5} \]


Do elongated vortices trap dust the same way?

Concentrated Vortex

\[ M_p = 1 \, M_{\text{Jup}} \quad T_{\text{growth}} = 10 \, \text{orbits} \quad \alpha_{\text{disk}} = 3 \times 10^{-5} \]

\[ t = 400 \, \text{orbits} \quad [m_p(t) = 1.00 \, M_{\text{Jup}}] \]

\begin{align*}
&0.00 & 0.25 & 0.50 & 0.75 & 1.00 & 1.25 & 1.50 & 1.75 & 2.00 & 2.25 & 2.50 \\
&0.15 & 0.30 & 0.45 & 0.60 & 0.75 & 0.90 & 1.05 & 1.20 & 1.35 & & \\
&1.10 & 1.20 & 1.30 & 1.40 & & & & & & & \\
\end{align*}

Elongated Vortex

\[ M_p = 1 \, M_{\text{Jup}} \quad T_{\text{growth}} = 1000 \, \text{orbits} \quad \alpha_{\text{disk}} = 3 \times 10^{-5} \]

\[ t = 845 \, \text{orbits} \quad [m_p(t) = 0.94 \, M_{\text{Jup}}] \]

\begin{align*}
&0.00 & 0.25 & 0.50 & 0.75 & 1.00 & 1.25 & 1.50 & 1.75 & 2.00 & 2.25 & 2.50 \\
&0.15 & 0.30 & 0.45 & 0.60 & 0.75 & 0.90 & 1.05 & 1.20 & 1.35 & & \\
&1.10 & 1.20 & 1.30 & 1.40 & & & & & & & \\
\end{align*}

Contour Levels: 1.10, 1.20, 1.30, 1.40, ..., 2.70
Azimuthal Density Profiles: \textbf{1 mm-size} grains

**Concentrated Vortex**

- Gaussian (as expected)

**Elongated Vortex**

- Mostly Flat! (not expected!)

Azimuthal Density Profiles: *1 cm*-size grains


Dust

Concentrated Vortex
- Gaussian (as expected)

Elongated Vortex
- Peak is off-center! (not expected!)
Why are the elongated vortex peaks off-center?

\[ M_p = 1 \, M_{\text{Jup}} \]

\[ T_{\text{growth}} = 1000 \text{ orbits} \]

\[ \alpha_{\text{disk}} = 3 \times 10^{-5} \]

The elongated vortex interacts with the planet’s spiral arms!

Synthetic Images of Elongated Vortices

$M_p = 1 \, M_{\text{Jup}}$
$R_p = 20 \, \text{AU}$
$T_{\text{growth}} = 1000 \, \text{orbits}$

$\alpha_{\text{disk}} = 3 \times 10^{-5}$

$s_{\text{min}} = 1 \, \mu\text{m}$
$s_{\text{max}} = 1 \, \text{cm}$
$n \sim s^{-3.0}$

$\lambda = 0.87 \, \text{mm (Band 7)}$
$d = 140 \, \text{pc}$

**Beam:** $0.07'' \times 0.07''$

**Signature:** Peak is off-center in images!

Resolving the Extent of an Elongated Vortex

A beam diameter of $0.5 \, r_p (0.07'' \times 0.07'')$ can resolve the extent and off-center peak of an elongated vortex.

Resolving the Extent of an Elongated Vortex

A beam diameter of $1.0 \, r_p \, (0.14'' \times 0.14'')$ can resolve the extent and off-center peak of an elongated vortex.

Resolving the Extent of an Elongated Vortex

A beam diameter of $1.5 \, r_p \,(0.21 \, \text{ʺ})$ cannot resolve an elongated vortex.

When observing vortex candidates, request beam sizes of at most the semimajor axis of the planet (not the asymmetry) in your ALMA proposal!

Summary

Jupiter analogs will not trigger vortices unless they can grow faster than the viscous accretion rate.

If giant planets can still trigger vortices, they would (1) have shorter lifetimes, (2) be less dense, and (3) be more elongated, making them less likely to observable.

Elongated planet-induced vortices are characterized by (1) wider azimuthal extents and (2) off-center peaks.

Beam diameters of at most the planet’s semimajor axis are needed to show that a vortex is elongated.
Generating Synthetic Images

(1) *Interpolate* from 6 grain sizes to 100 grain sizes from 1 μm to 1 cm.

(2) *Combine* all grain sizes into a single surface density map.

[Grain Size Distribution: \( n = n_0 s^{-3.0} \) ]

(3) *Run* radiative transfer calculations to convert the density map into a simulated intensity map.

(4) *Convolve* simulated images with a beam size.
Do larger grains in elongated vortices still have narrower concentrations? (Yes.)
Resolving the Extent of an Elongated Vortex

Azimuthal Extents at $I/I_0 = 0.5$

- $T_{\text{growth}} = 10$
- $T_{\text{growth}} = 1000$
- Difference

$\phi_{\text{extent}}$ (degrees) vs. Beam Diameter ["]
Two-Fluid (Gas + Dust) Simulations

To simulate this with Two-Fluid FARGO (Zhu, Z. et al. 2012):

(1a) Start with a gas disk with the left radial density profile.
(1b) Start with a dust disk with same profile, but 100x lower density.
(2) Then, add a giant planet at $r = 1$ and run the simulation.

Particle Sizes: 1 μm, 100 μm, 0.3 mm, 1 mm, 0.3 cm, 1 cm
<table>
<thead>
<tr>
<th>Mass</th>
<th>Viscosity</th>
<th>Planet Growth Times</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(“Instant”)</td>
</tr>
<tr>
<td>1 $M_{Jup}$</td>
<td>$\alpha = 3 \times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>1 $M_{Jup}$</td>
<td>$\alpha = 3 \times 10^{-5}$</td>
<td>10</td>
</tr>
<tr>
<td>5 $M_{Jup}$</td>
<td>$\alpha = 3 \times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>5 $M_{Jup}$</td>
<td>$\alpha = 3 \times 10^{-5}$</td>
<td>10</td>
</tr>
</tbody>
</table>

(in orbits)
Vortex Lifetimes with Slower Planet Growth

When are gap edges unstable?

High-Viscosity disks \((\alpha \geq 3 \times 10^{-3})\) will smooth out these peaks.

Low-Viscosity disks \((\alpha < 3 \times 10^{-3})\) are needed to form vortices.