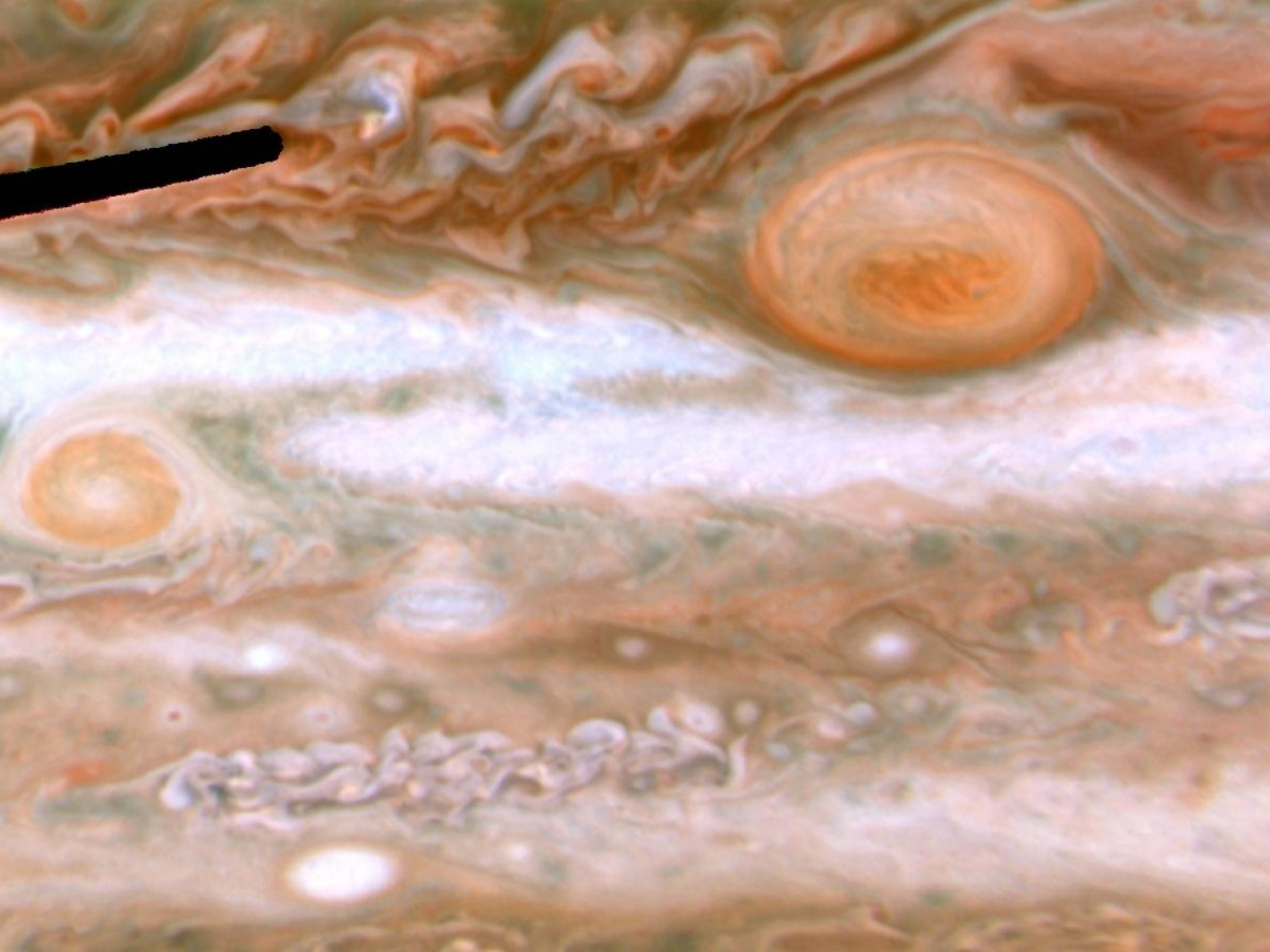
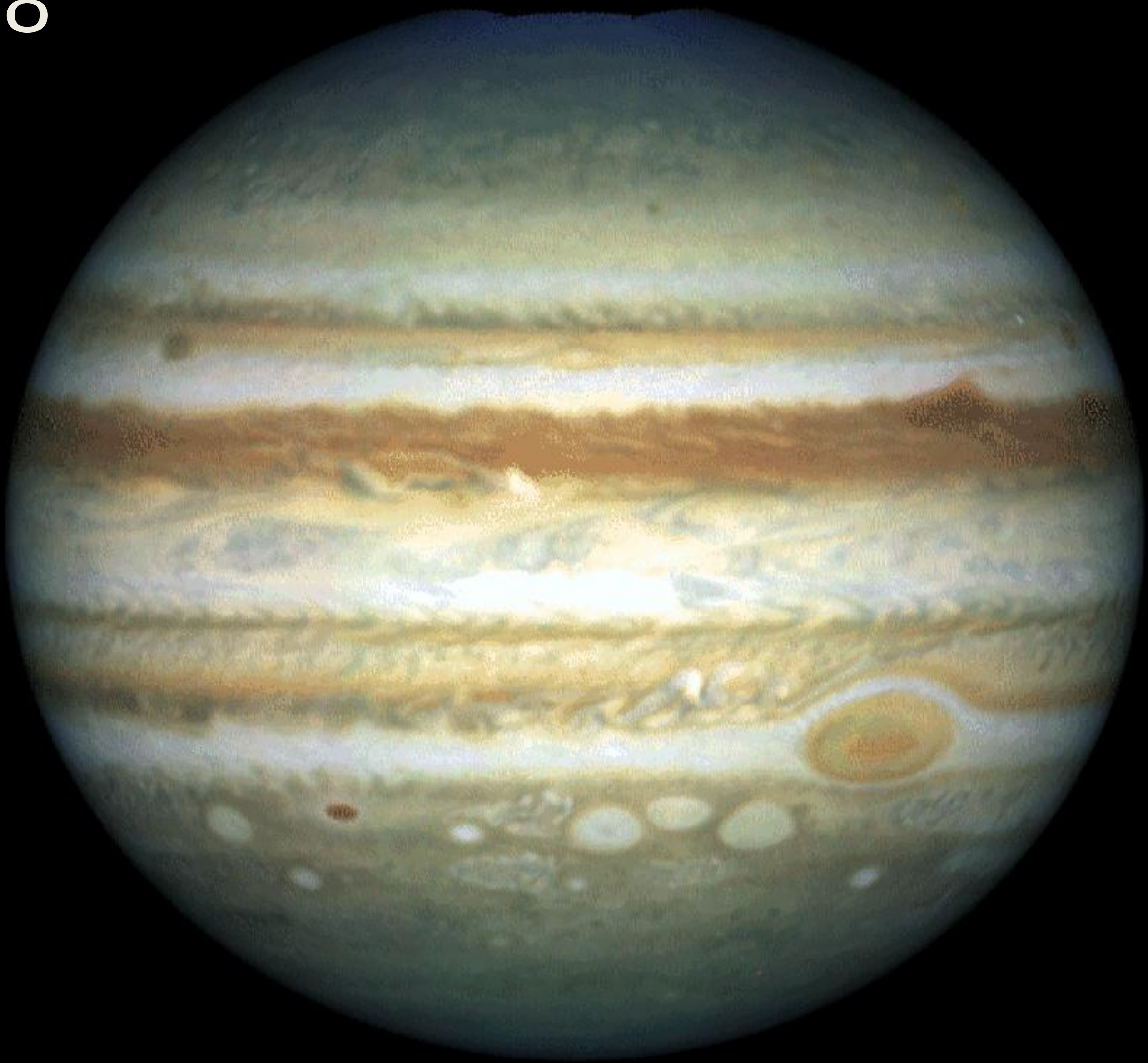
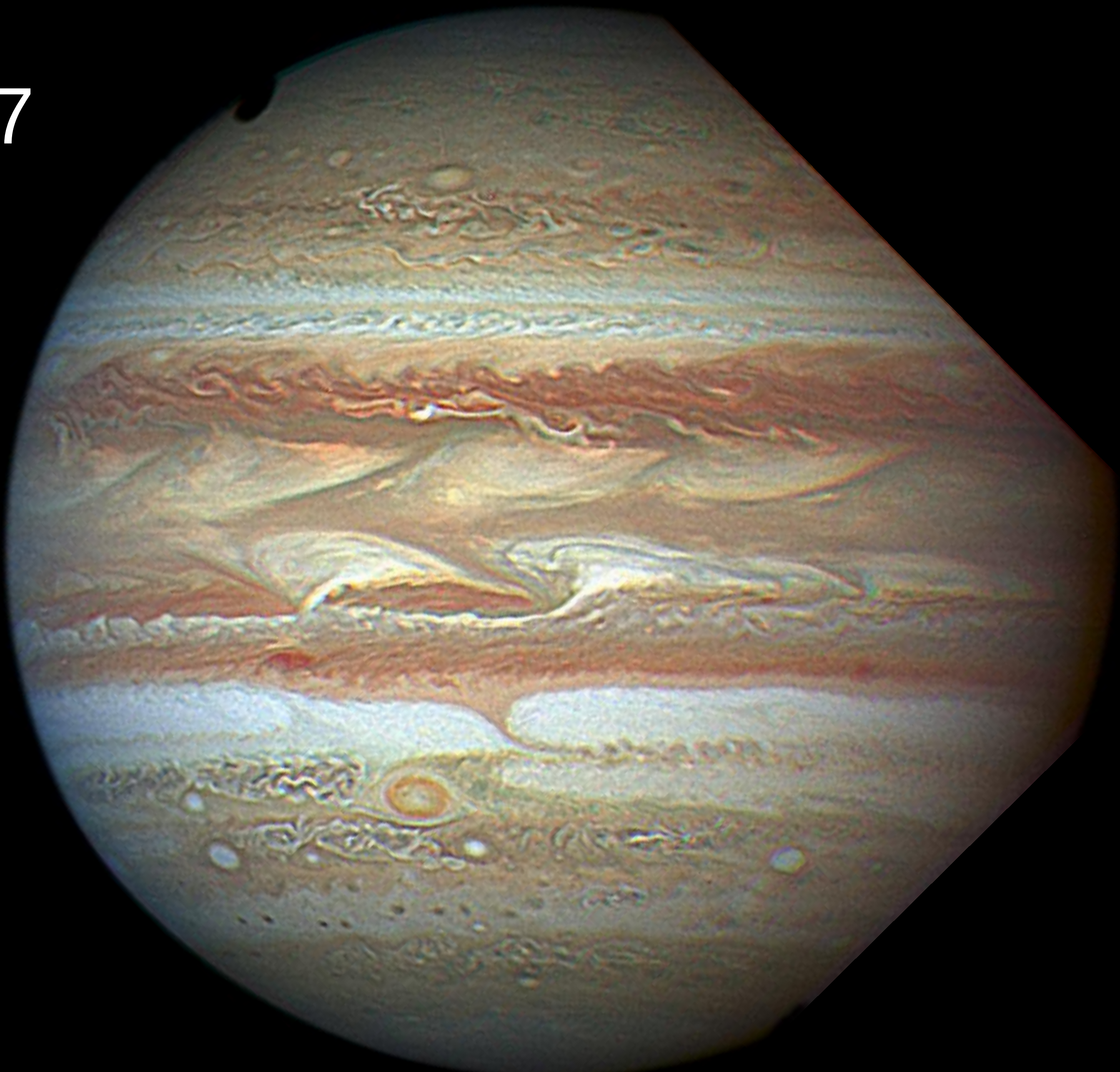


1998



2007



SCIENCE

New Pictures Show Jupiter Is Missing a Stripe

Updated: 10 days 15 hours ago

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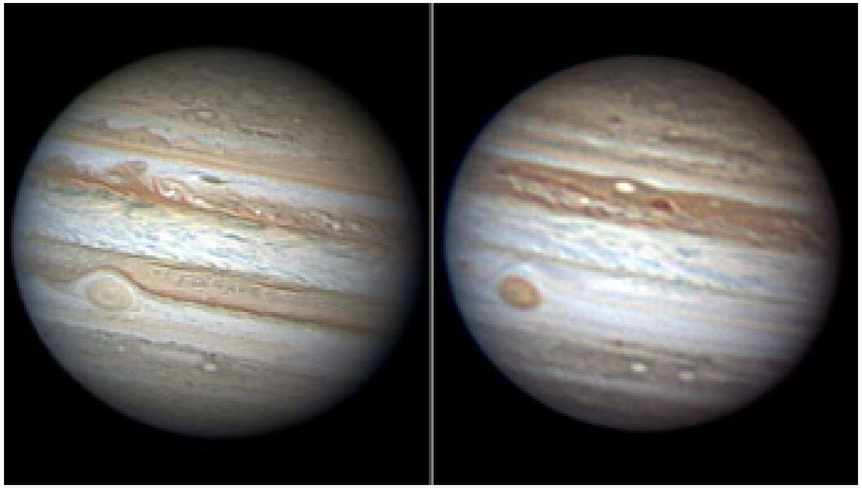
Hugh Collins

(May 13) -- New pictures of Jupiter show that a huge band of dark clouds that normally surrounds the giant planet has vanished.

The planet's appearance usually is dominated by two dark bands in its atmosphere -- one in the north and another in the south -- along with the Giant Red Spot, an enormous storm that is more than twice the size of Earth.

All three were visible at the end of last year before the planet went behind the sun. When it re-emerged last month, new pictures from Australian astronomer Anthony Wesley showed the southern cloud band was nowhere to be seen.



Anthony Wesley, The Planetary Society

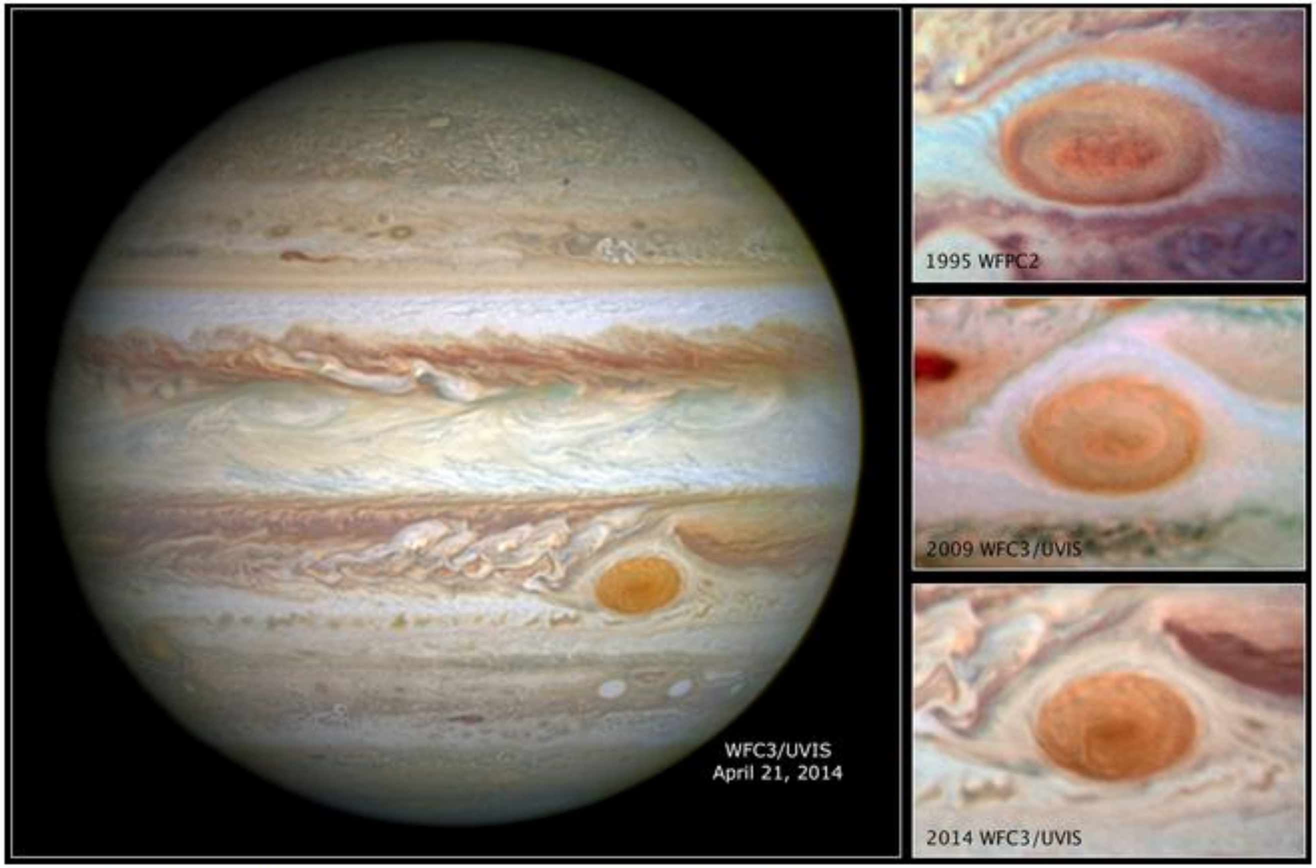
The photo at left shows Jupiter without the band of clouds that typically circles it south of its famous Giant Red Spot. The photo at right shows the cloud belt intact.

"It just doesn't look right," amateur astronomer Bob King of Duluth, Minn., wrote on his blog AstroBob. "Jupiter with only one belt is almost like seeing Saturn when its rings are edge-on and invisible for a time."

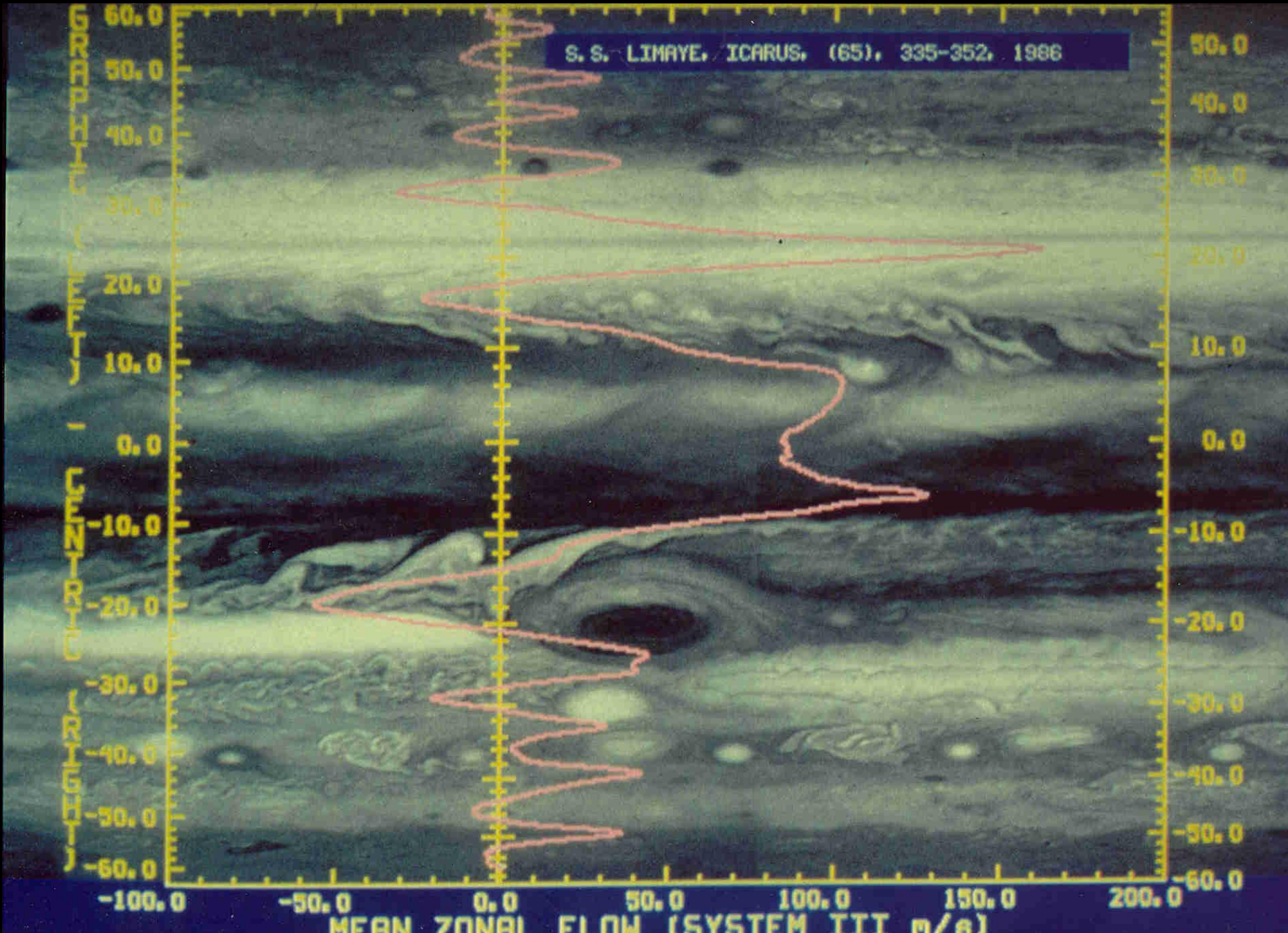
This is not the first time the southern band has gone missing. It

The Washington Post

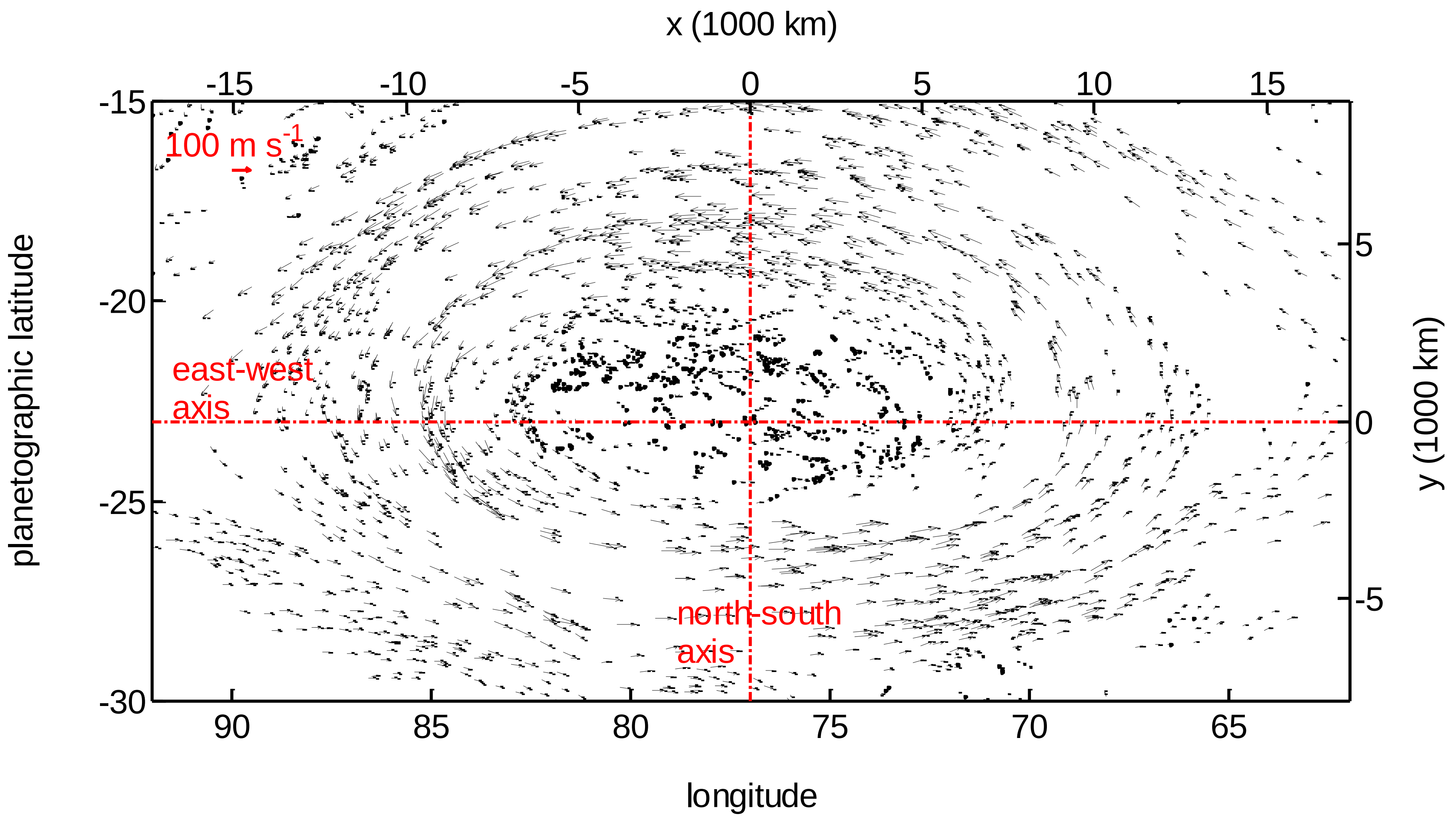
Jupiter's red spot is mysteriously shrinking



It's definitely shrinking, but no one knows why. (NASA/ESA)


S.S. LIMAYE, ICARUS, (65), 335-352, 1986
GRAPHIC (LEFT) - CENTRIC (RIGHT)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
MEAN ZONAL FLOW (SYSTEM III m/s)

“By hand” Velocity Extraction



Jet Streams, Vortices & Turbulence

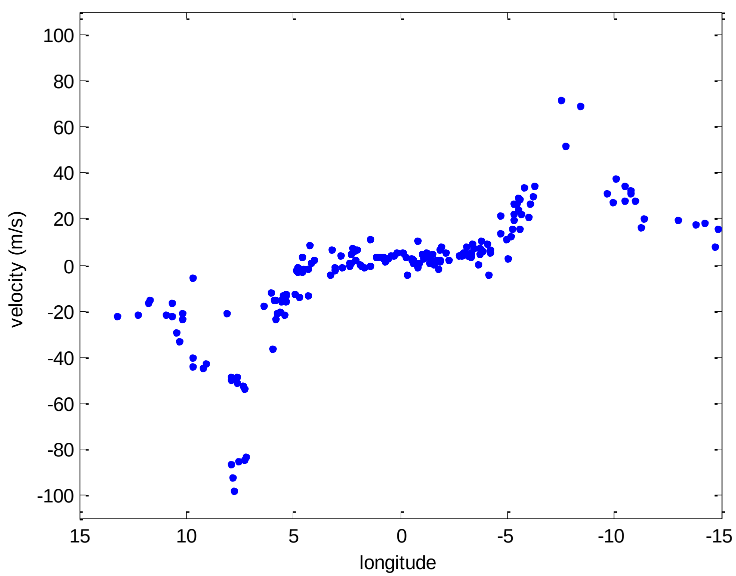
- 12 Eastward-going and 12 Westward-going jet streams ~50-100m/sec
- Long-lived vortices
  - Red Spot, (3 White Ovals ⟶ 1 red spot junior)
  - 90% are Anti-Cyclones
- Turbulence is ~2 m/sec

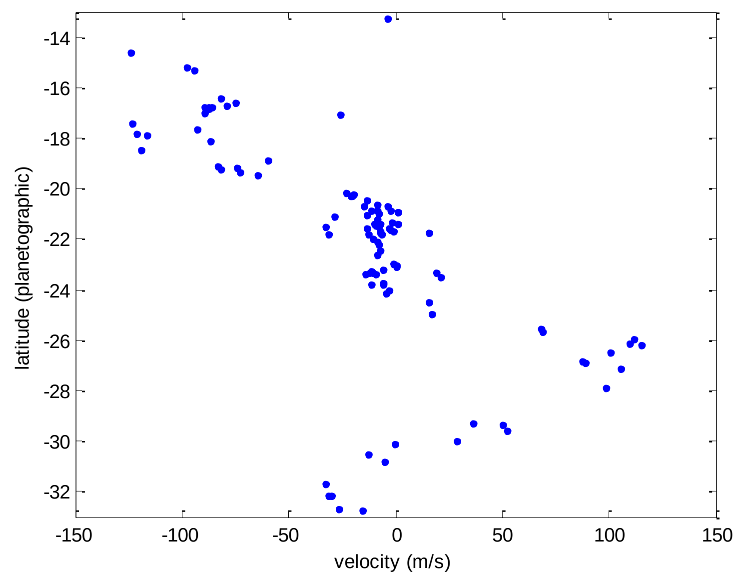
Remote Sensing

- Are Long-Lived Clouds Vortices?
- If so, are the cyclones or anticyclones?
- Can there be long-lived vortices that are not associated with clouds?

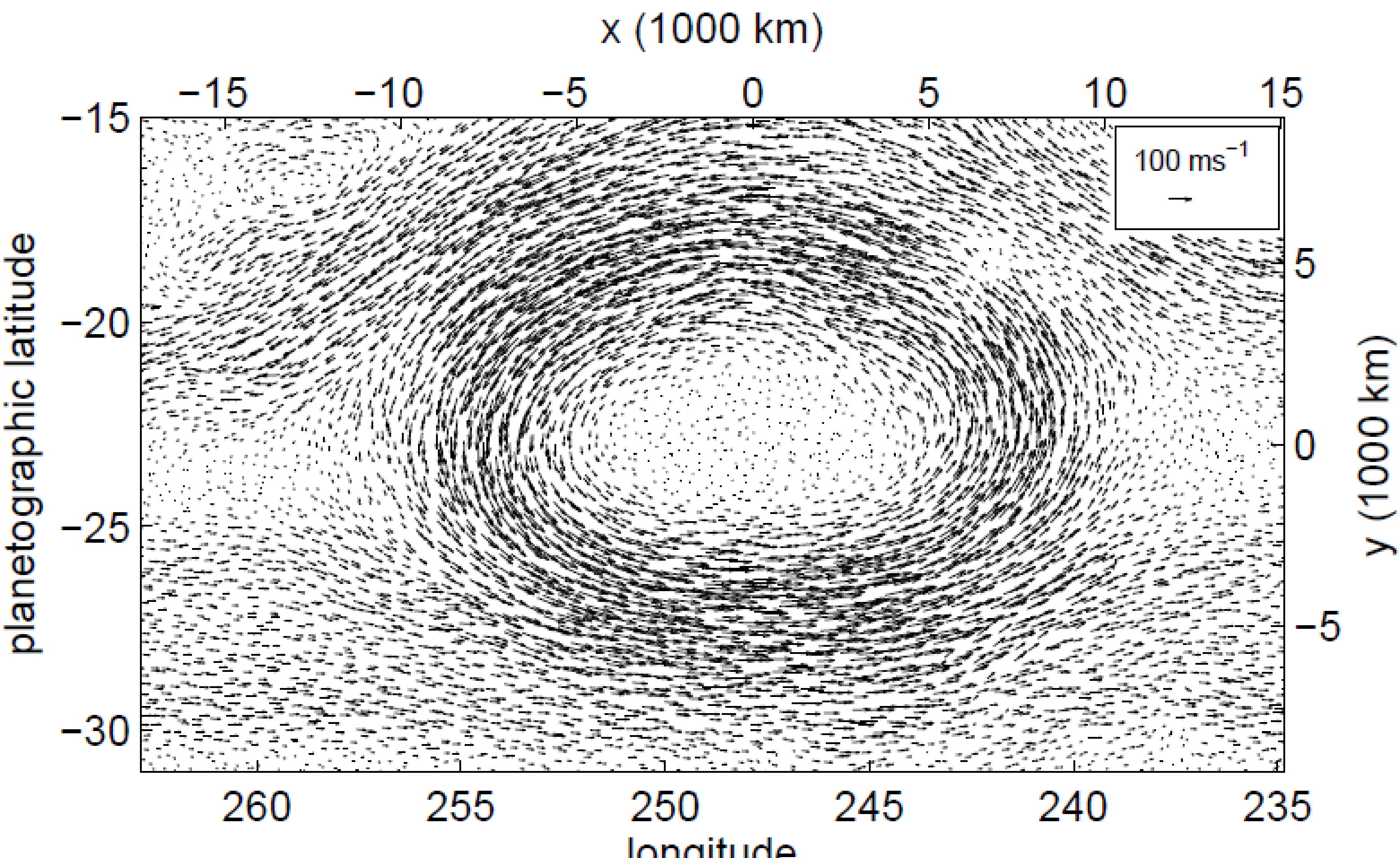
Manual Cloud Tracking GRS

- 10 hours tracks ~10^3 velocity vector
- too few vectors
- Uncertainty ~10 m/s

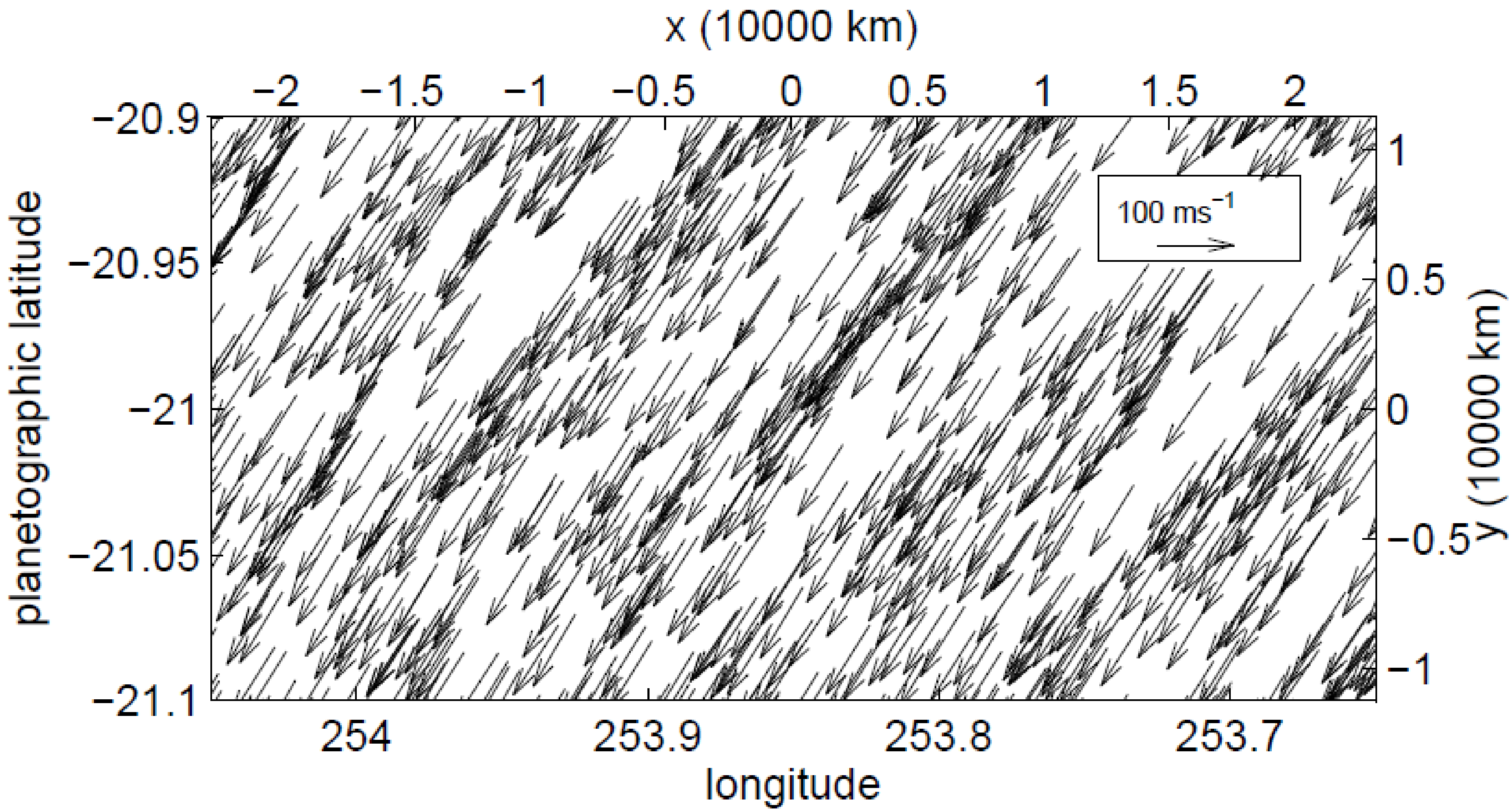




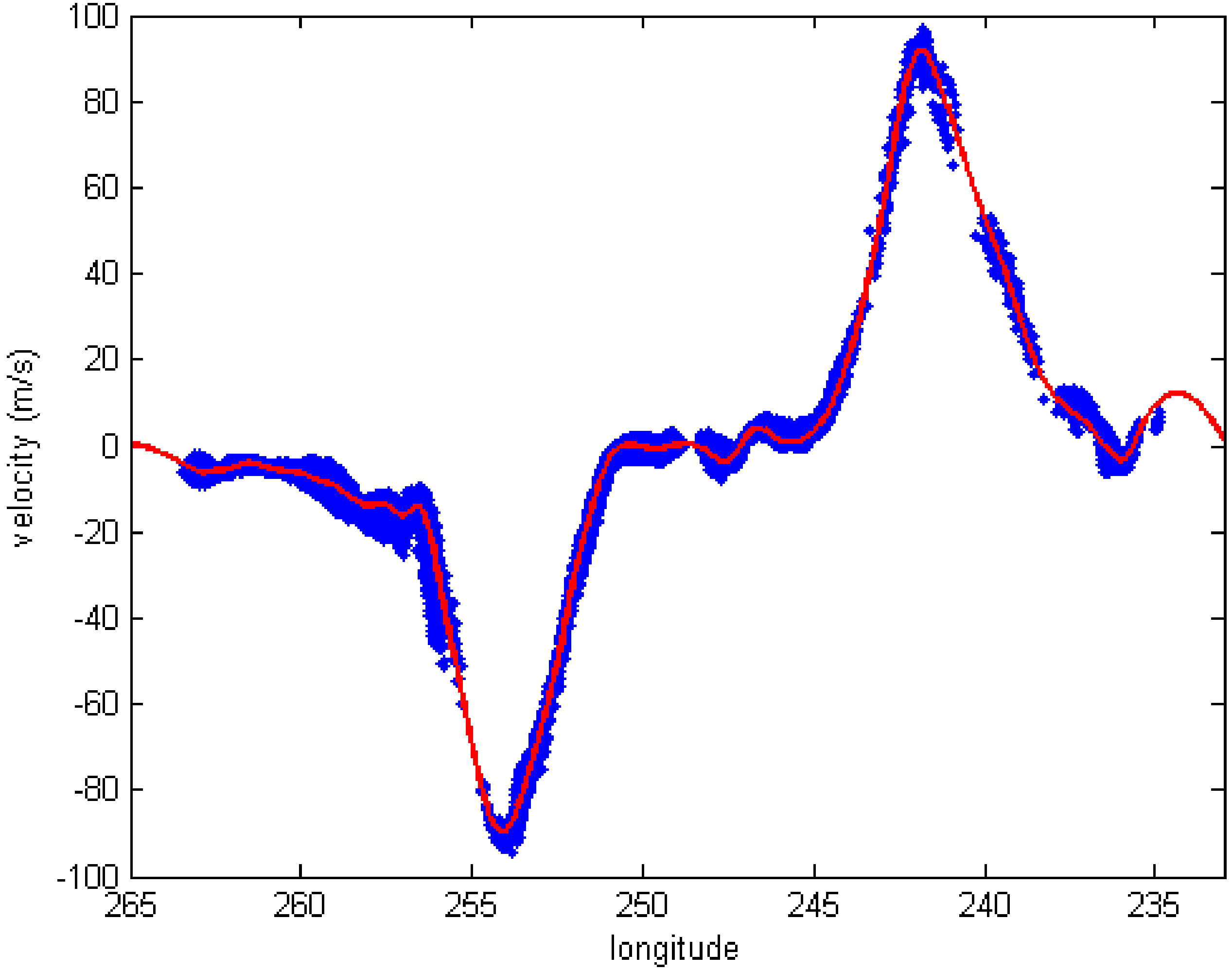
~10,000 of the 1.6 million velocity vectors of the GRS



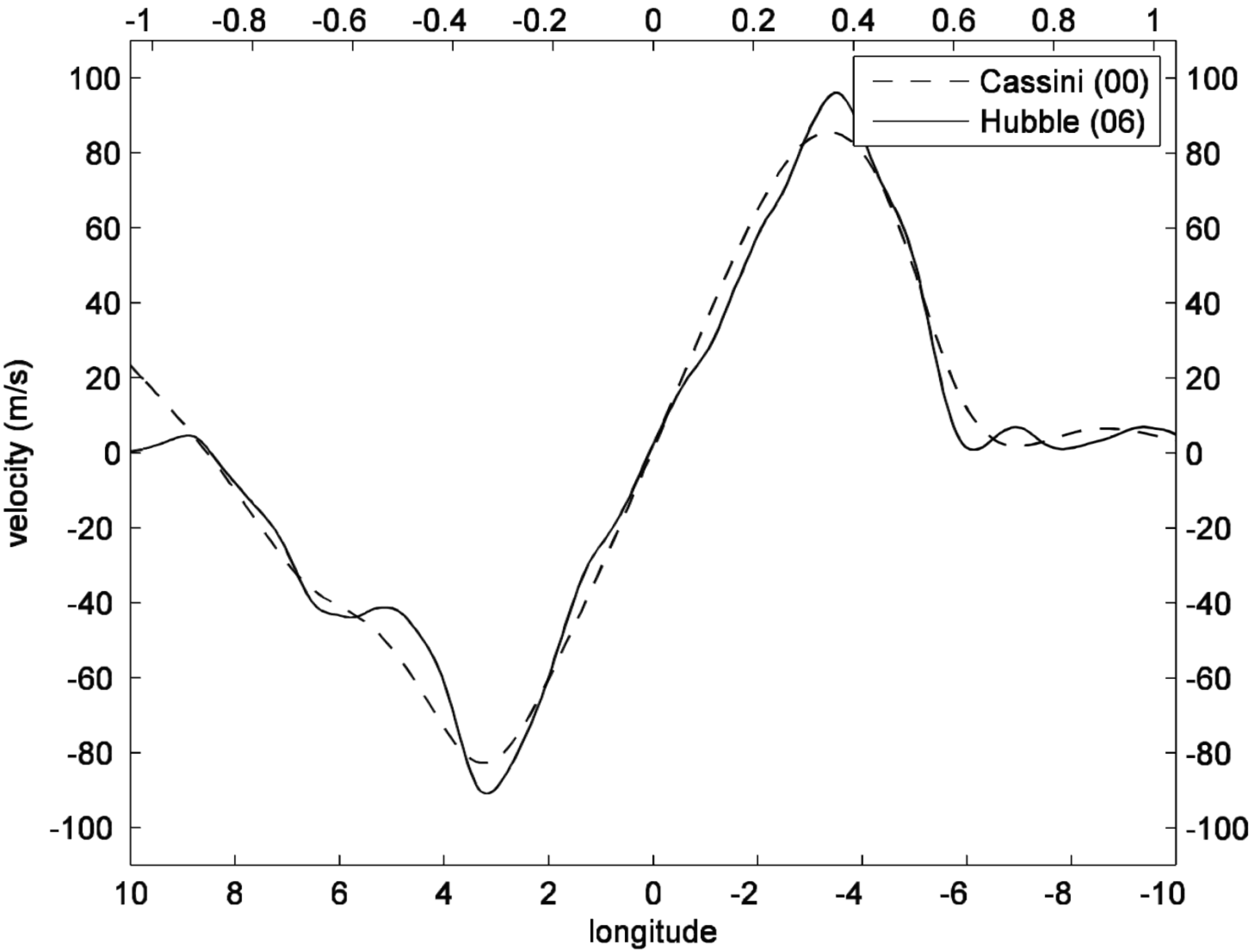
0.2° X 0.5° box showing all velocity vectors



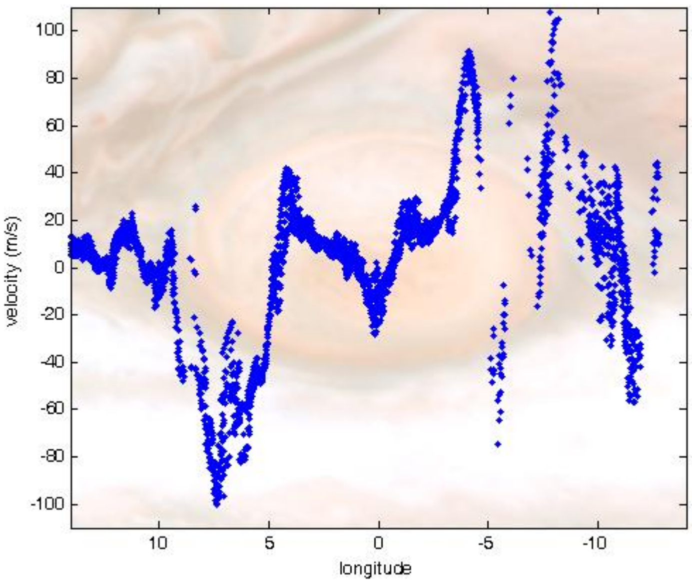
GRS with ACCIV Algorithm

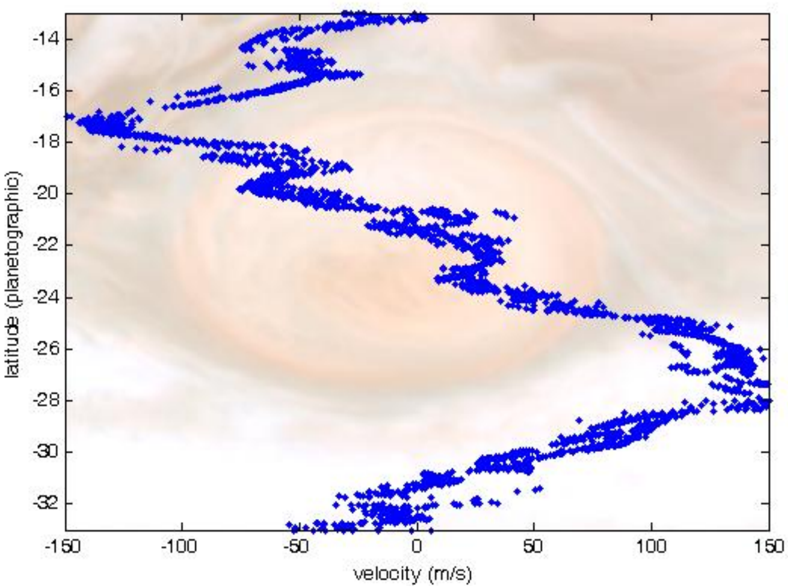


Oval BA Velocity Cross Section

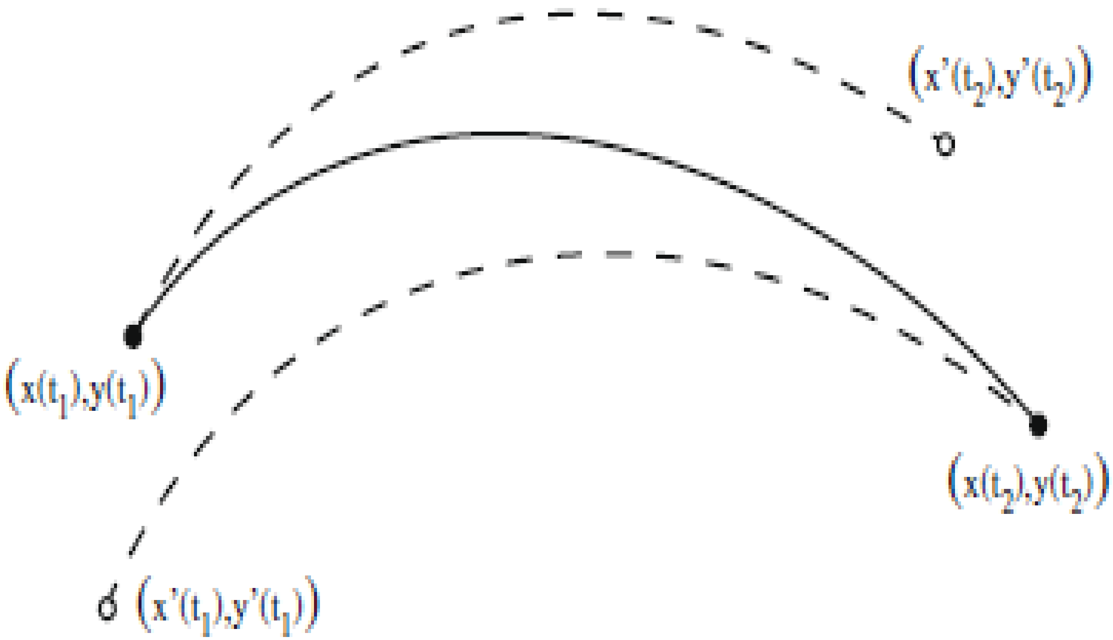


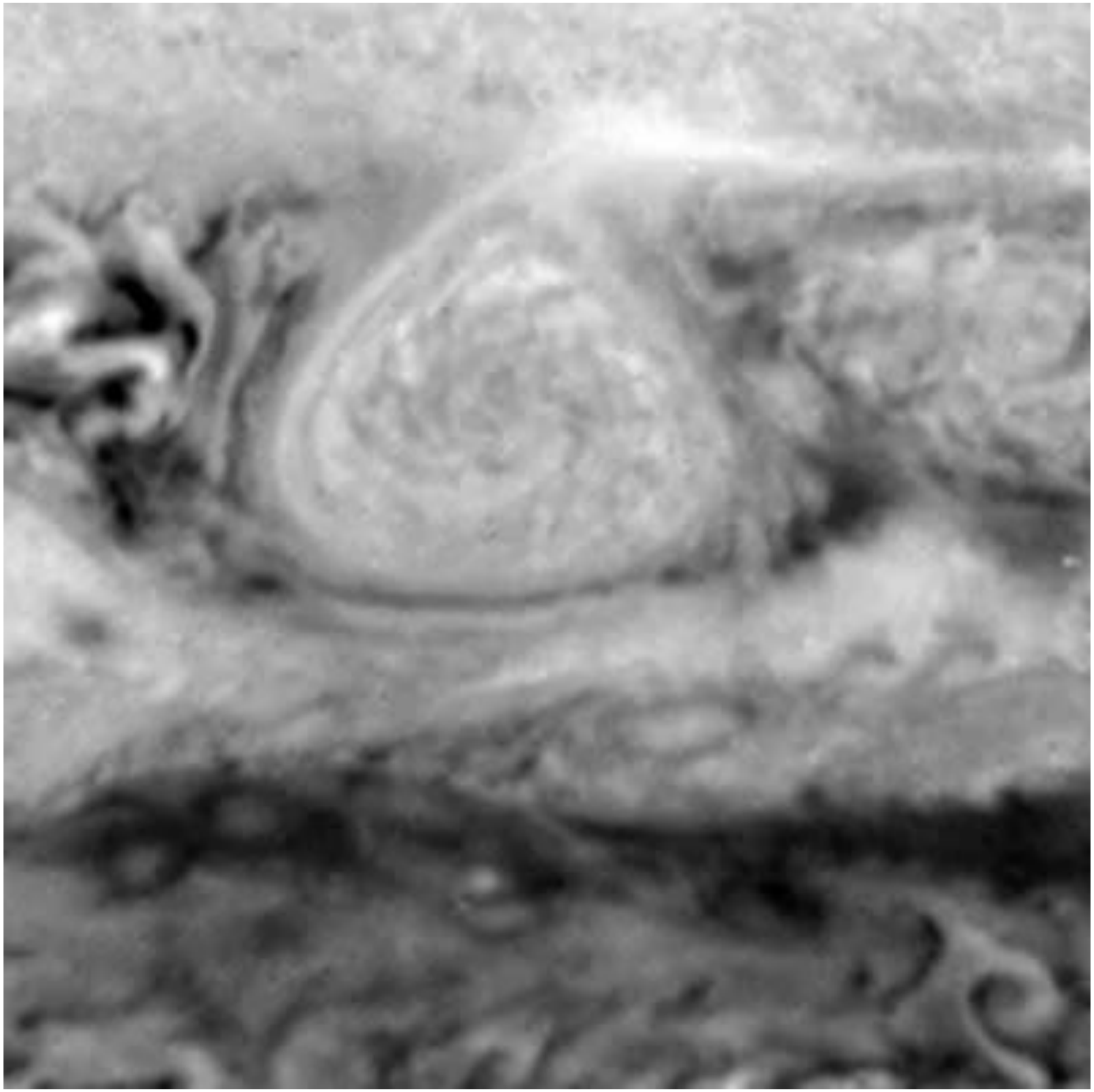
CIV – GRS, 40 minutes

- From Hubble images at 658 nm wavelength
- ~10^5 velocity vectors
- 

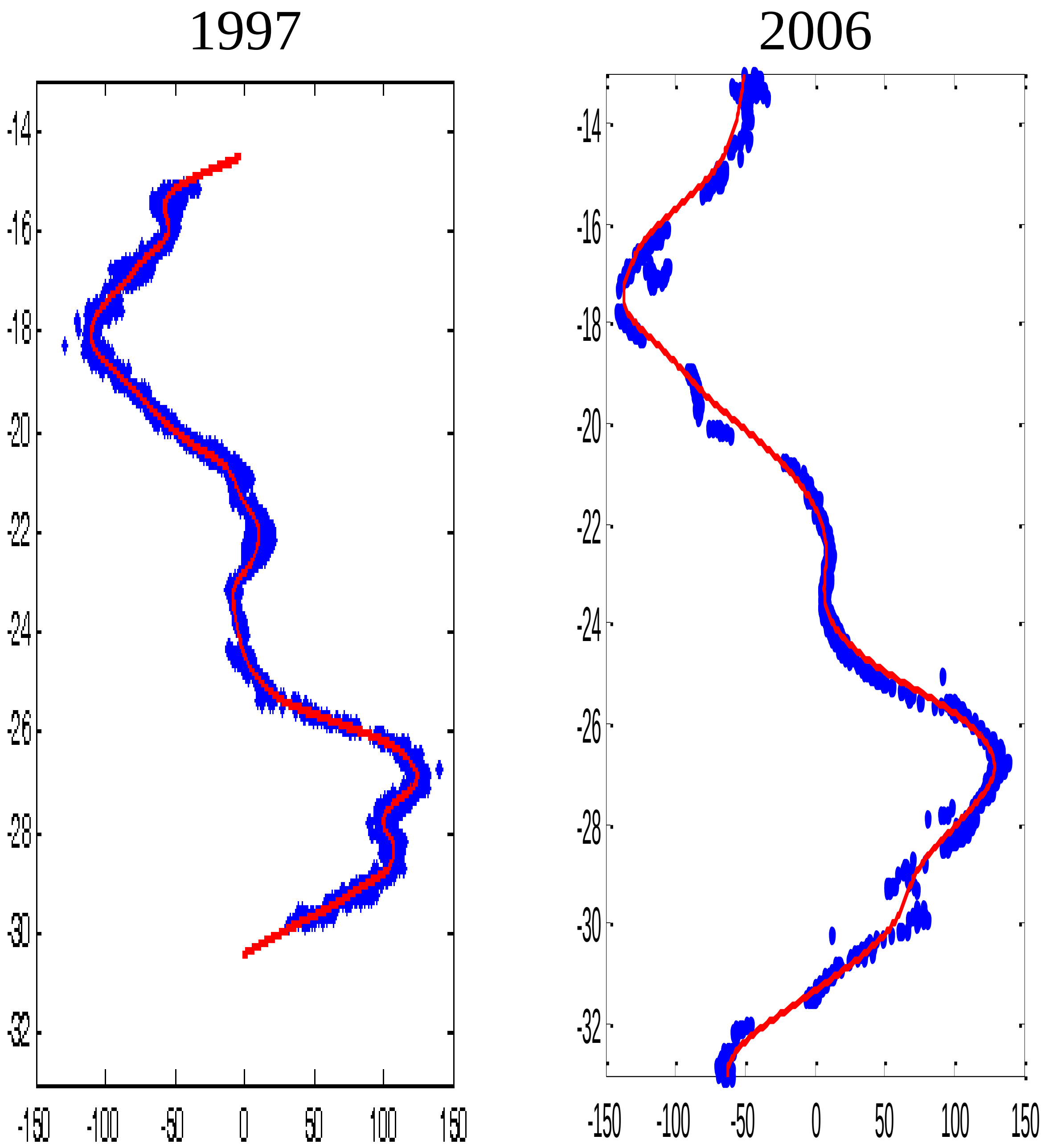


Advection-Correction



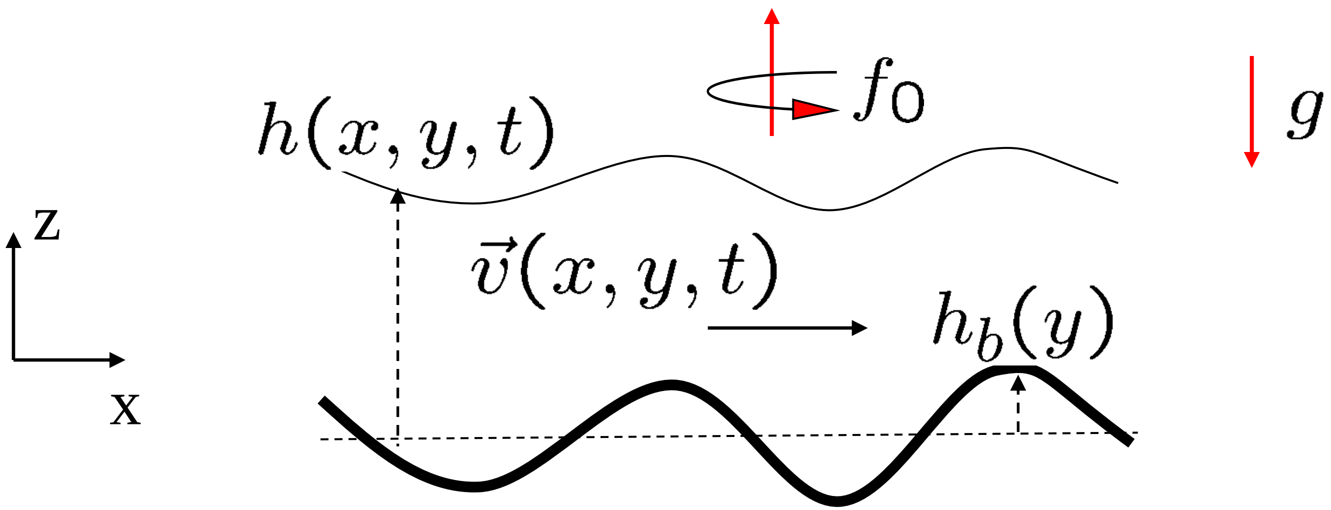


New Red Oval 10 hours


1997
2006
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-150
-100
-50
0
50
100
150

Dynamical equations

1.5-layer Quasi-Geostrophic equations



Potential vorticity *q* is advectively conserved:

$$\frac{\partial q}{\partial t} + \vec{v} \cdot \nabla q = 0$$

$$q(x,y,t) \equiv \left(\nabla^2 - \frac{1}{L_r^2} \right) gh(x,y,t)/f_0 + \left(\frac{1}{L_r^2} \right) gh_b(y)/f_0$$

$$\vec{v}(x,y,t) = \hat{z} \times \nabla gh(x,y,t)/f_0$$

Vorticity is known but not PV

- Velocity field derived by tracking motion of discrete cloud features using Advection-Corrected-Correlation-Image-Velocimetry

  (*Asay-Davis et. al.*, *Icarus*, *2009*)
- Typically yields 10^6 independent velocities with fractional uncertainties ~ 5% and vorticity with uncertainties of 10%
- However, the deformation radius and $h_b(y)$ are not known
- $\partial q / \partial t = -(\mathbf{V}\cdot\nabla)\, q$ is satisfied by all zonal velocities when *PV* is a function only of *y*

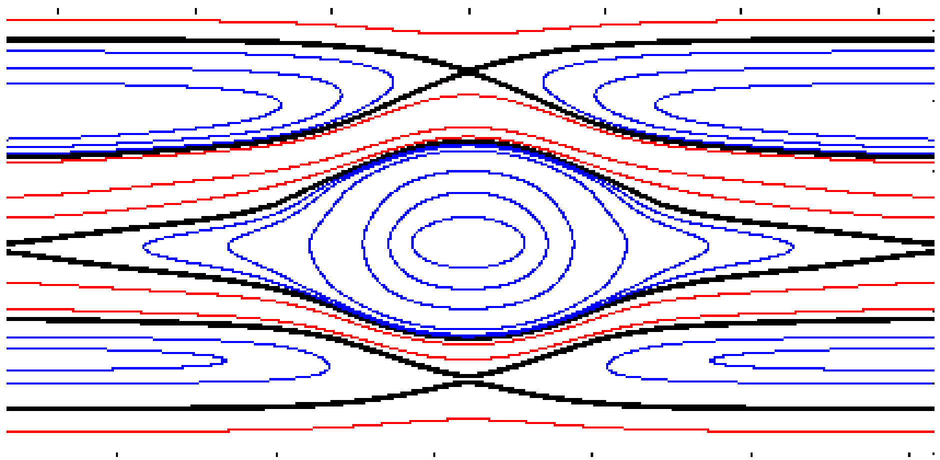
Finding $h_b(y)$ and L_r by Solving an Inverse Problem

- Fast-solver for steady state and/or uniformly translating) solutions
- $0 = (\mathbf{V}\cdot\nabla)\, q$
- $0 = (\mathbf{V}\cdot\nabla)\, \{\omega(x,y,t) - \psi(x,y,t)/L_r^2 + [g h_b(y)/f_0]\, /L_r^2 + \beta y\}$
- Use genetic algorithm.

  Shetty & Marcus *Icarus* 2010 **210** 182-201
- Typically, reproduces observations, to within the observational uncertainties.
- Uncertainties found by Monte Carlo Bootstrap

Geometry of a Jovian-vortex solution

- Streamline topology for a Jovian-vortex solution is characterized by open streamlines, closed streamlines, and stagnation point streamlines.



$$(\vec{v} - U\hat{x}) \cdot \nabla q = 0$$

- => streamlines in vortex frame are coincident with iso-contours of potential vorticity.

- Jovian-vortex solution can be parameterized in terms of potential vorticity along just two lines:

Geometry of a Jovian-vortex solution

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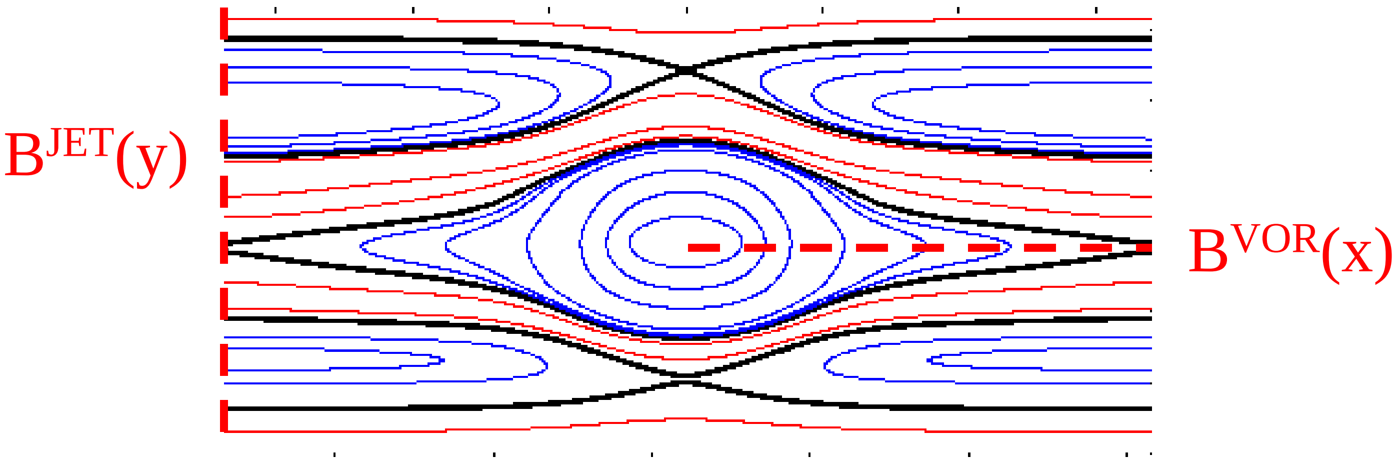
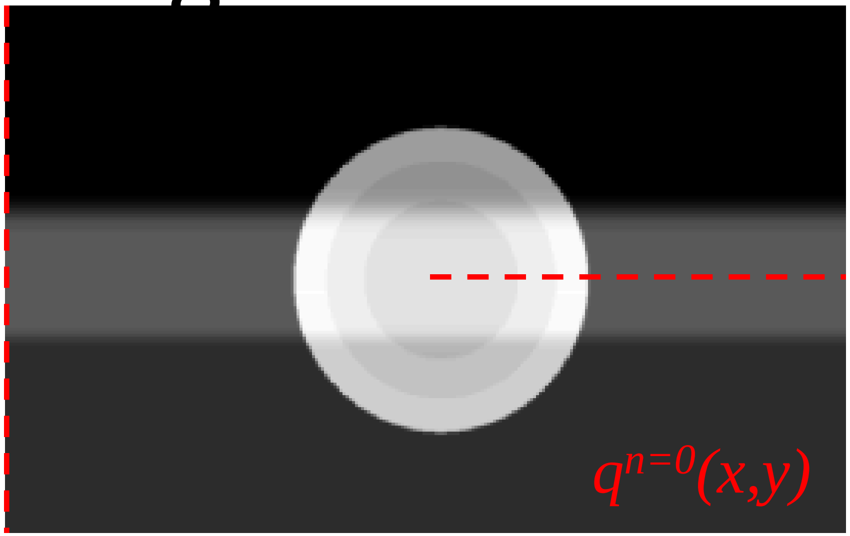


- $(\vec{v} - U\hat{x}) \cdot \nabla q = 0$ => streamlines of in vortex frame are coincident with iso-contours of potential vorticity.

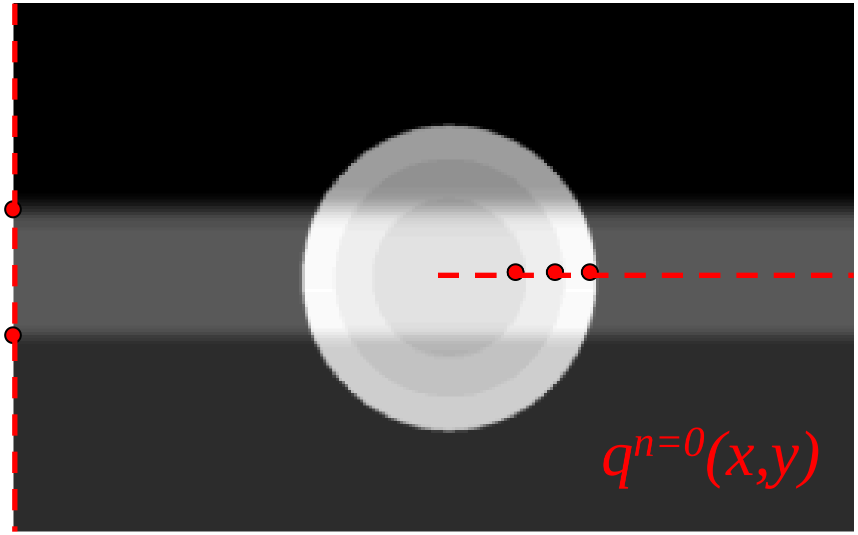
- Jovian-vortex solution can be parameterized in terms of potential vorticity along just two lines:
  - $B^{JET}(y)$ and $B^{VOR}(x)$
  - Still need L_r and $h_b(y)$.

Fast-solver algorithm

Generate initial guess for vortex PV and jet-stream PV consistent with boundary functions



"Discretize" boundary functions with tracer particles



Fast-solver algorithm

Compute velocity field from potential vorticity by inverting Helmholtz operator.

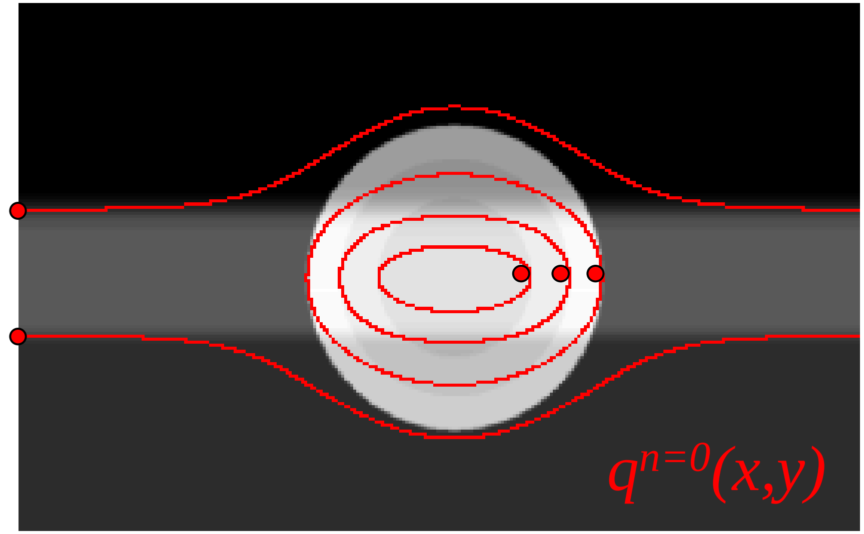
Compute drift velocity of vortex:

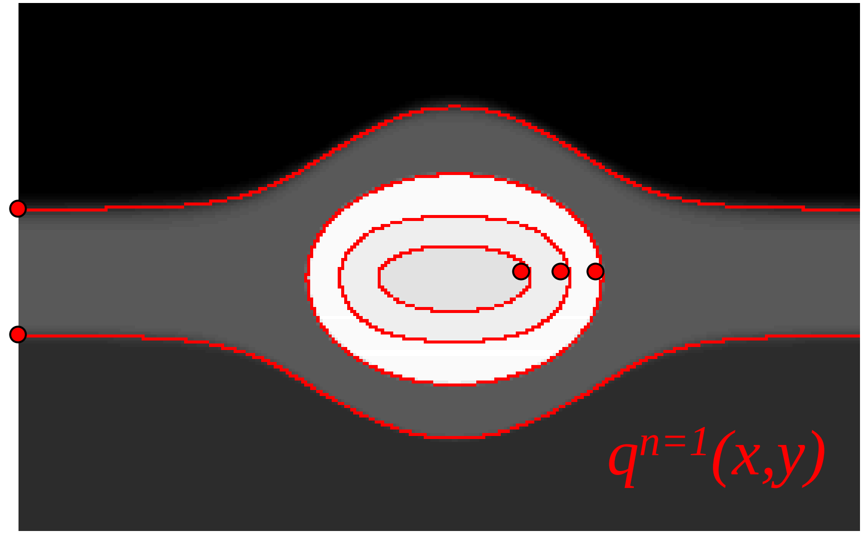
$$U^n = \frac{\int (q^{VOR})^n (\vec{v}^n \cdot \hat{x}) dxdy}{\int (q^{VOR})^n dxdy}$$

In vortex frame, compute streamline passing through each tracer particle.

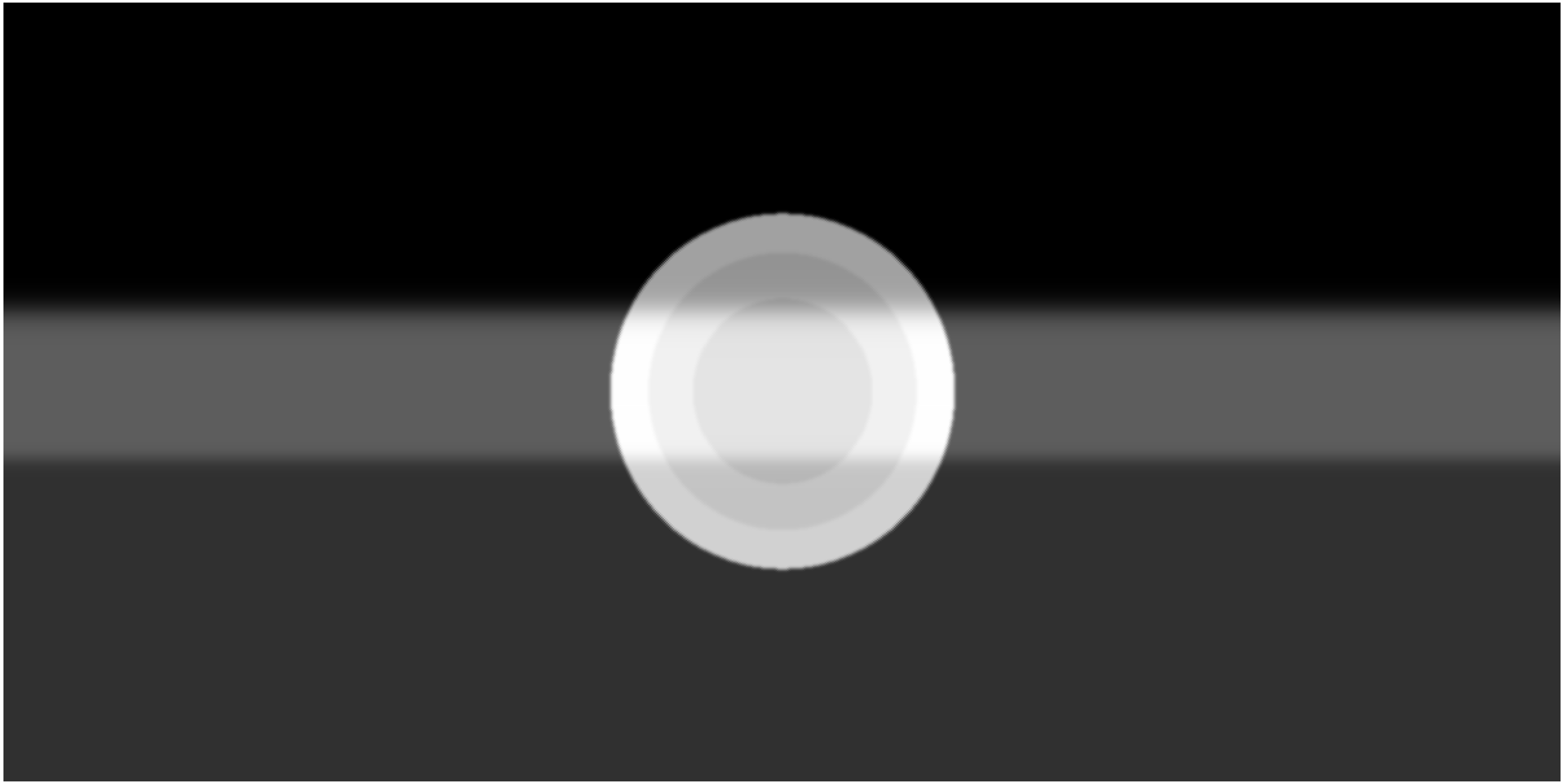
Set potential vorticity along each streamline to potential vorticity of boundary function at location of tracer particle.

Repeat until convergence.

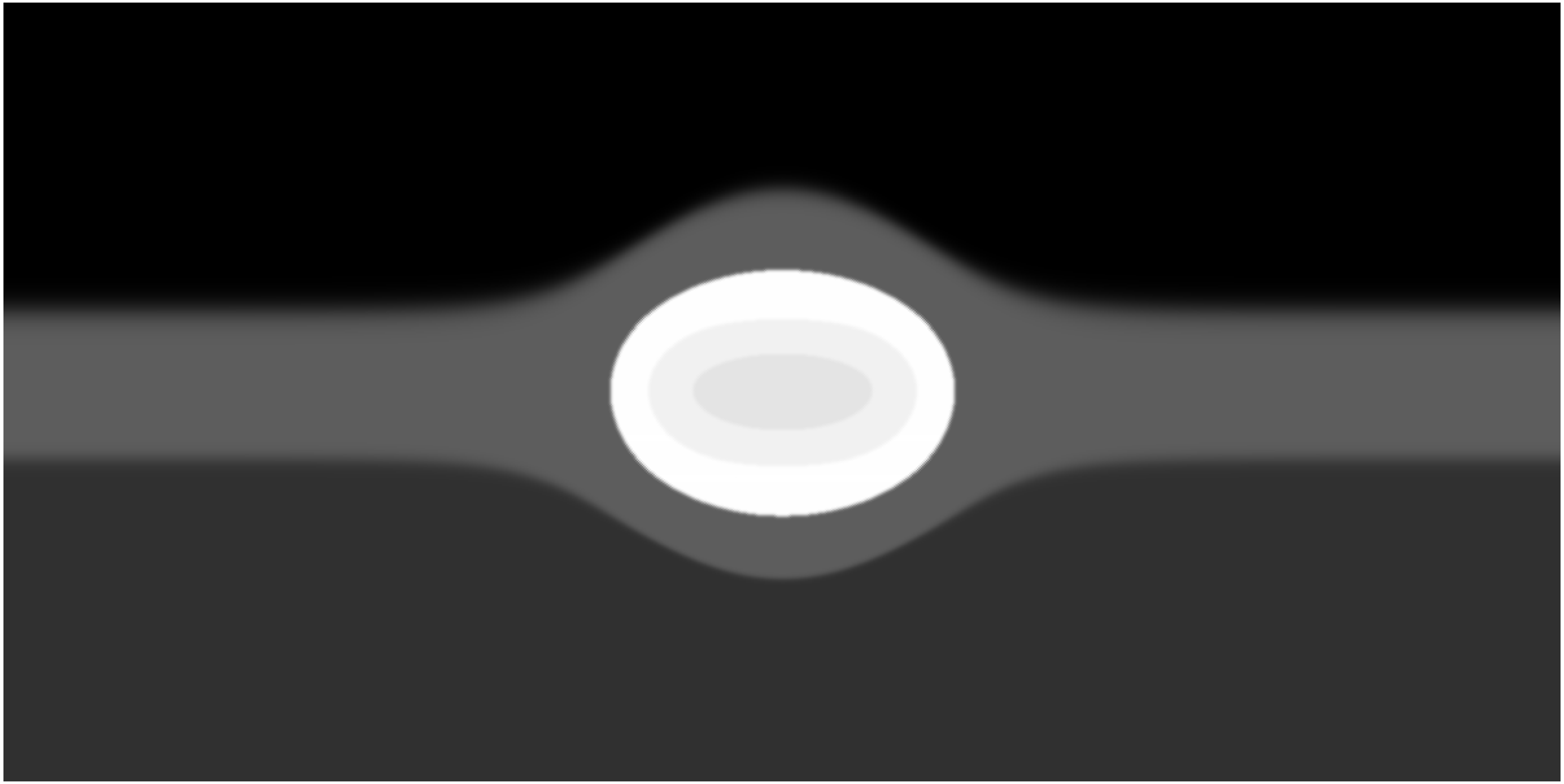




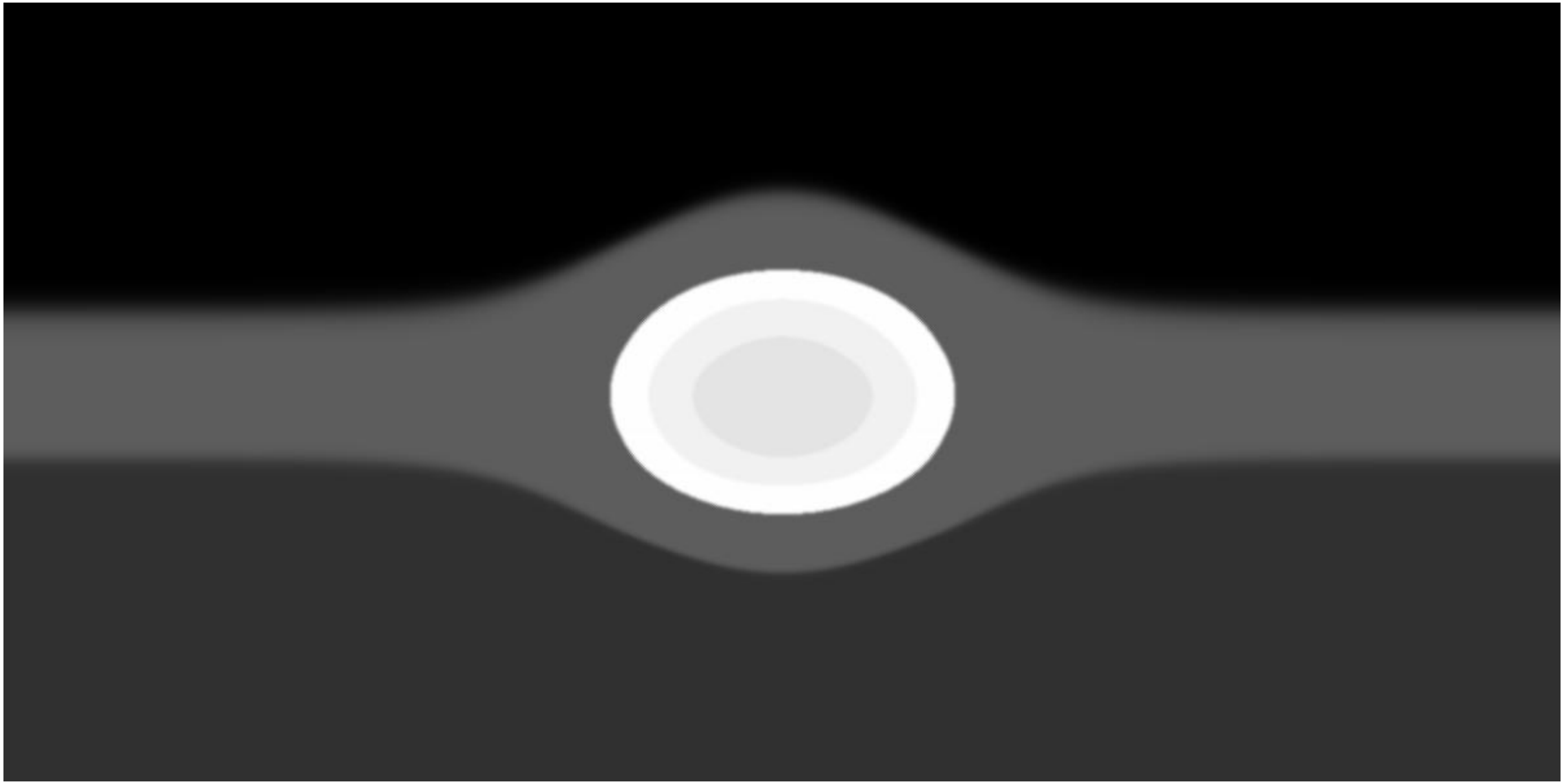
Fast-solver example (n=0)



Fast-solver example (n=1)

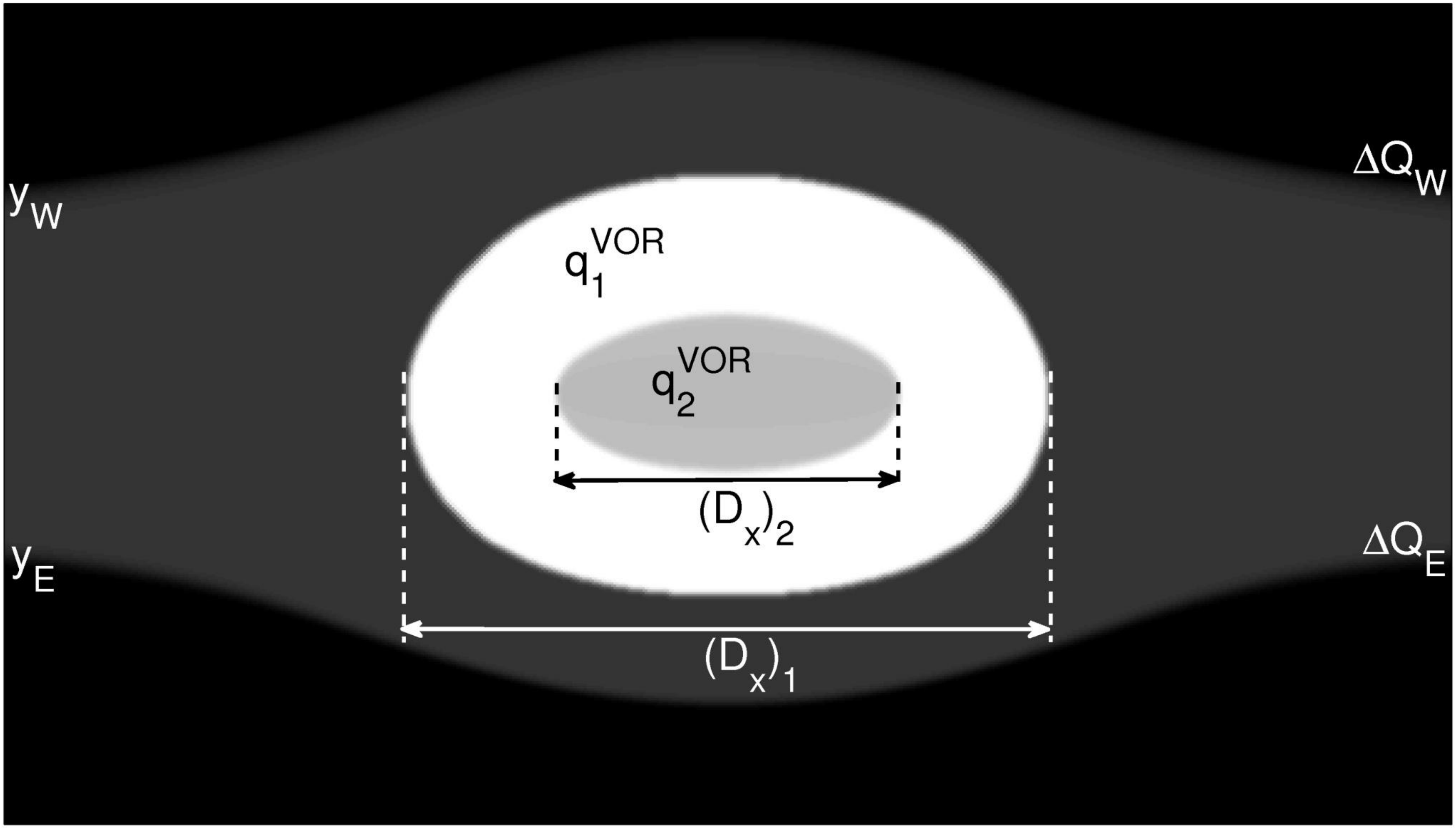


Fast-solver example (n=2)



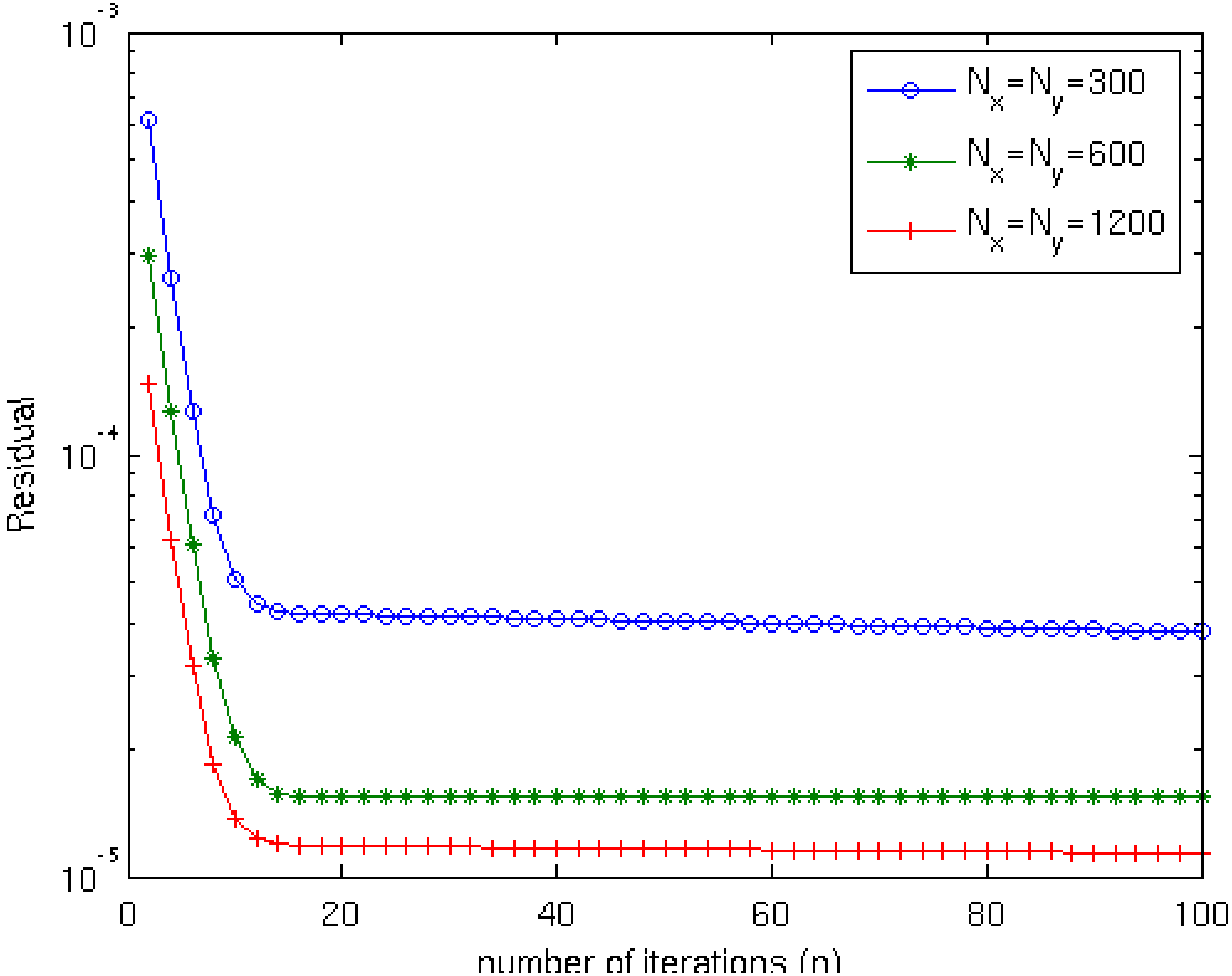
Fast-solver example (n=3)

Fast-solver example (n=4)



y_W
ΔQ_W
q_1^{VOR}
q_2^{VOR}
$(D_x)_2$
y_E
ΔQ_E
$(D_x)_1$

Fast-solver is efficient



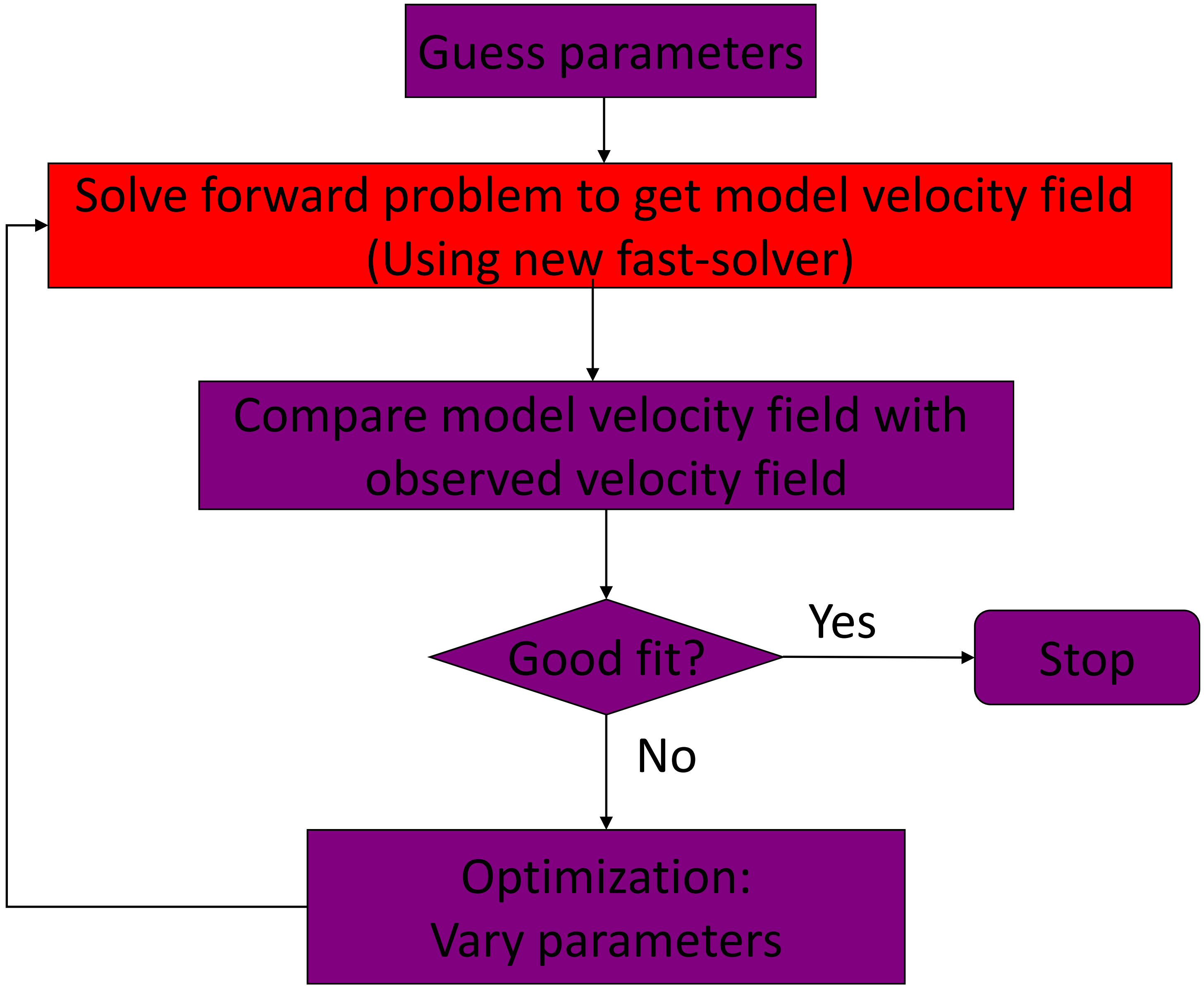
$$\text{Residual} \equiv ||(\vec{v} - U\hat{x}) \cdot \nabla q||_2 / (||\vec{v} - U\hat{x}||_2 ||\nabla q||_2)$$

Genetic-algorithm

- Genetic-algorithms explore parameter space through *mutation*, *re-combination*, and *natural selection*.

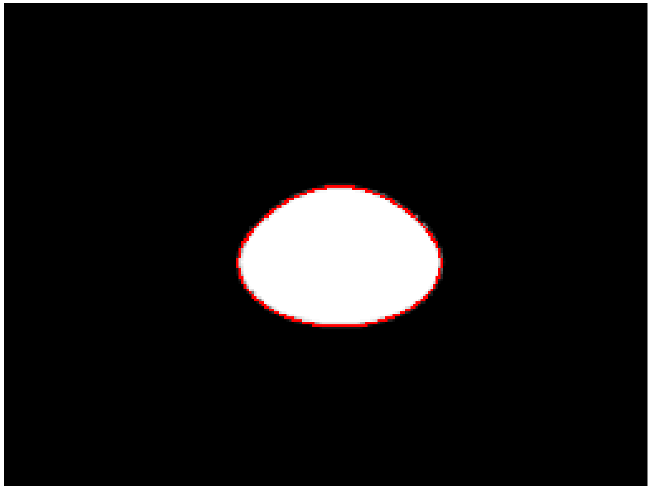
- Used here because:
  - Convexity of cost-function cannot be established
  - Jovian-vortex solutions may not exist far from best-fit => cost-function non-smooth

Overview of new method

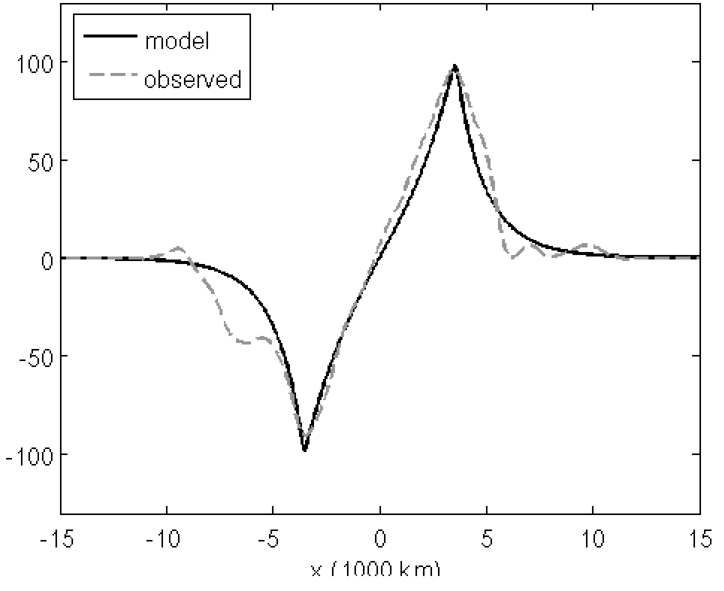


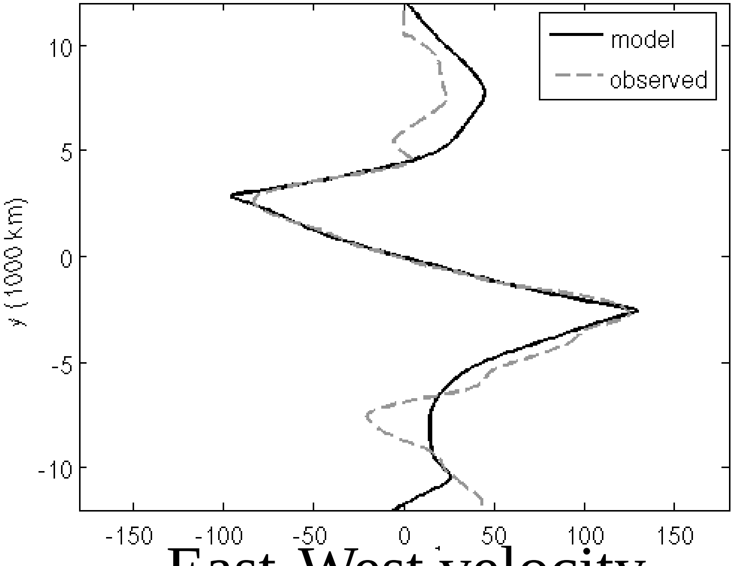
Inversion results for Oval

- Best-fit model for $N^{JET}=0$, $N^{VOR}=1$.
- *L_r = 1900 km* ± *200 km*
- RMS Error (model) = 10.4 ms^{-1}
- RMS Error (obs.) = 5.5 ms^{-1}



North-South velocity

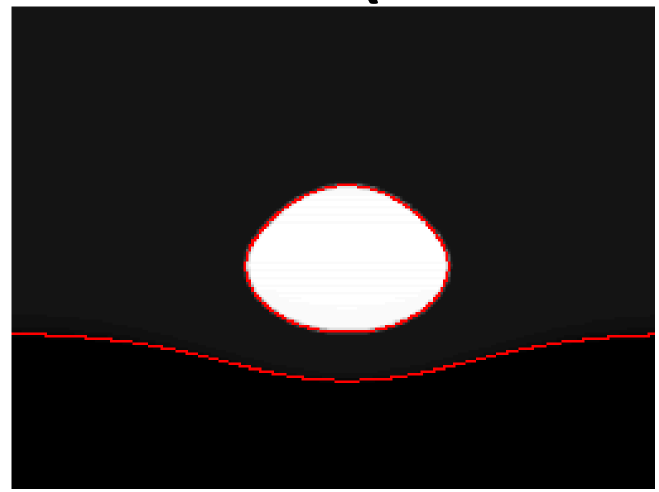


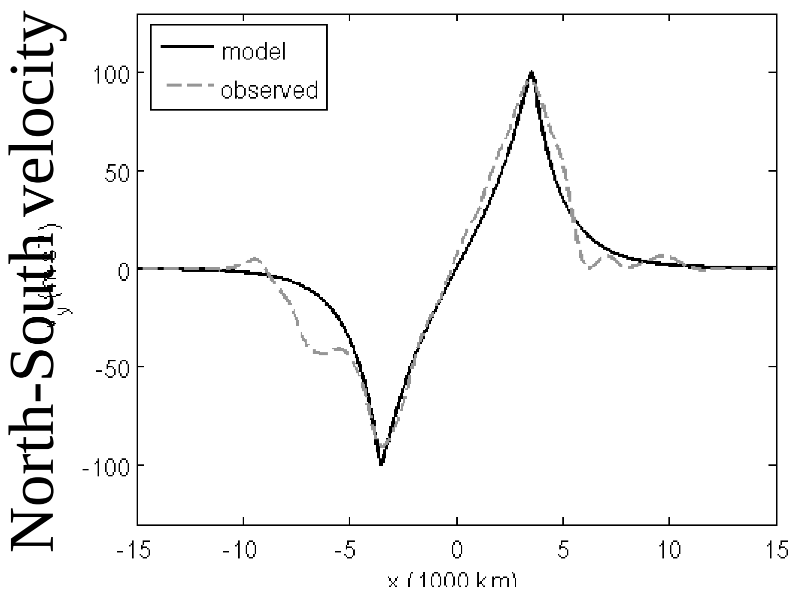


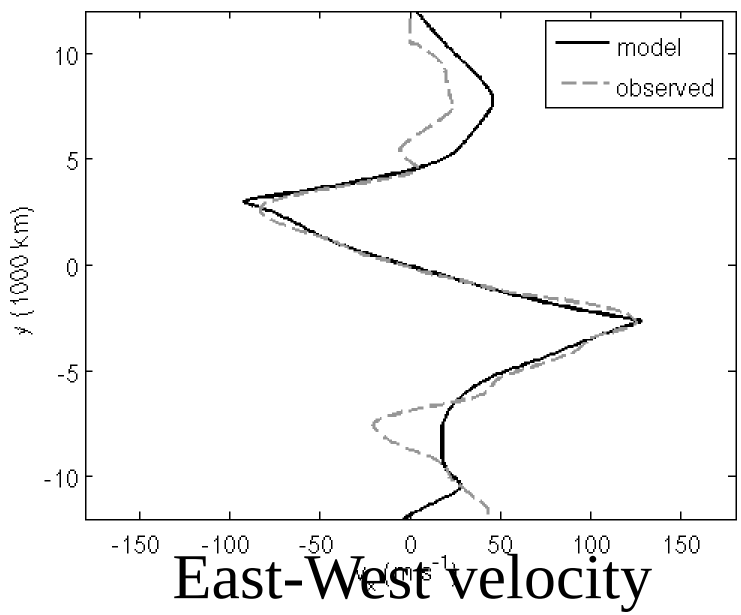
East-West velocity

Inversion results for Oval (contd.)

- Best-fit model for $N^{JET}=1$, $N^{VOR}=1$.
- *L_r = 1900 km* ± *150 km*
- RMS Error (model) = 9.4 ms^{-1}
- RMS Error (obs.) = 5.5 ms^{-1}

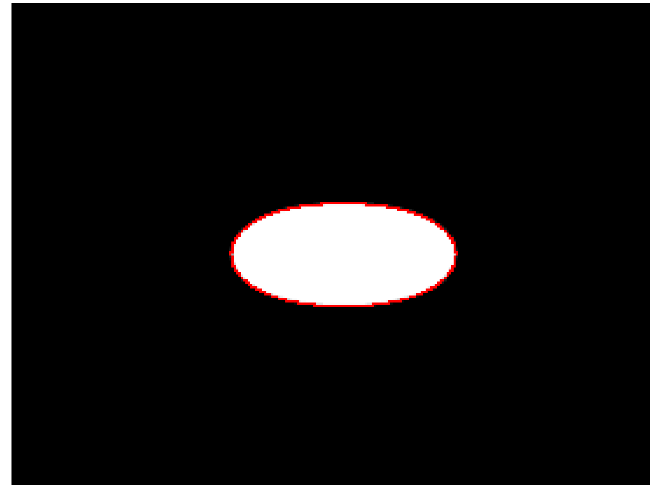


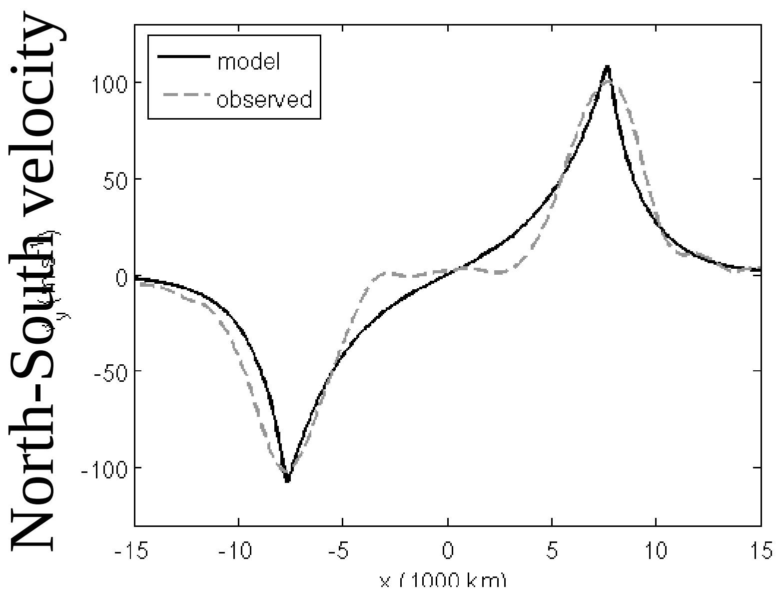


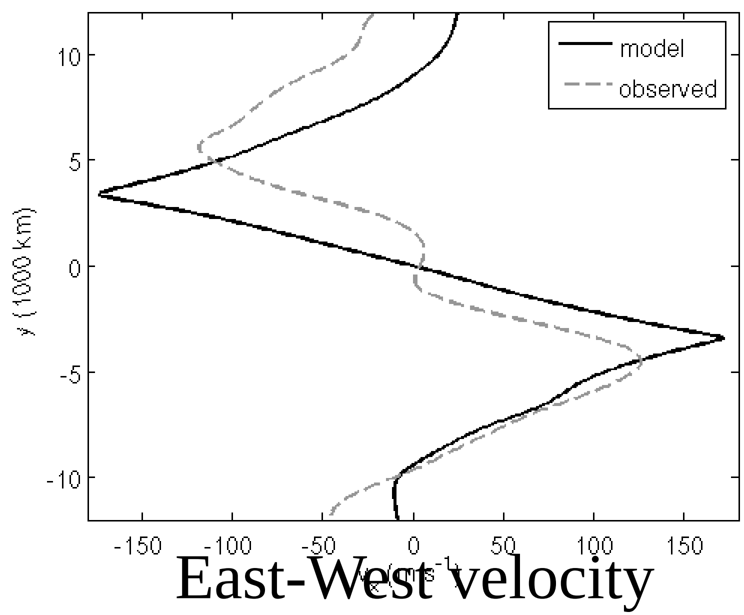


Inversion results for GRS

- Best-fit model for N^{JET}=0, N^{VOR}=1.
- *L_r = 2200 km 100 km*
- RMS Error (model) = 25 ms^{-1}
- RMS Error (obs.) = 4.5 ms^{-1}

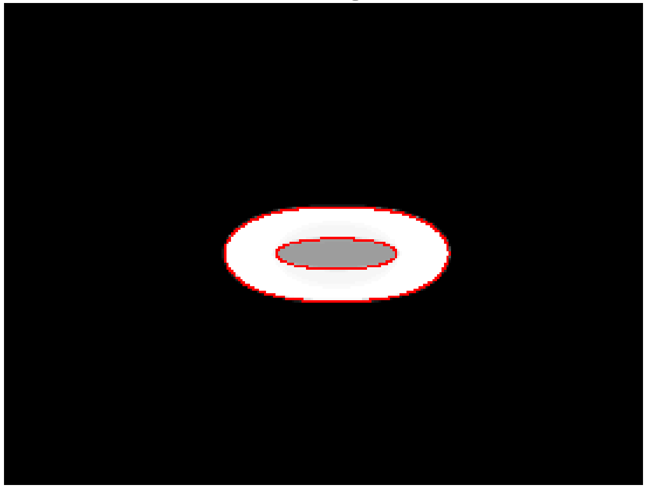


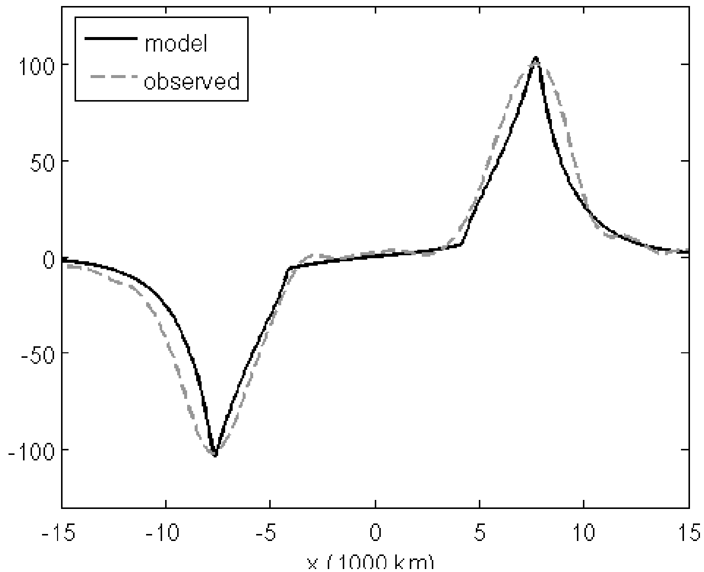




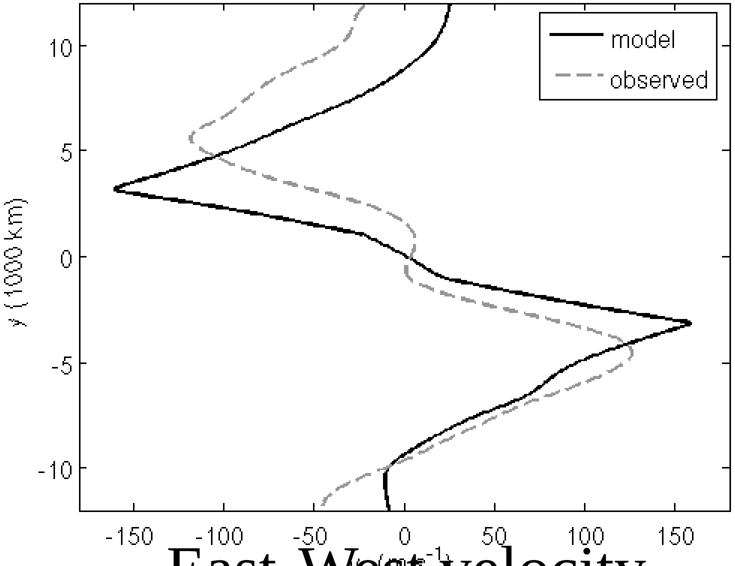
Inversion results for GRS (contd.)

- Best-fit model for $N^{JET}=0$, $N^{VOR}=2$.
- *L_r = 2250 km ± 100 km*
- RMS Error (model) = 24 ms^{-1}
- RMS Error (obs.) = 4.5 ms^{-1}





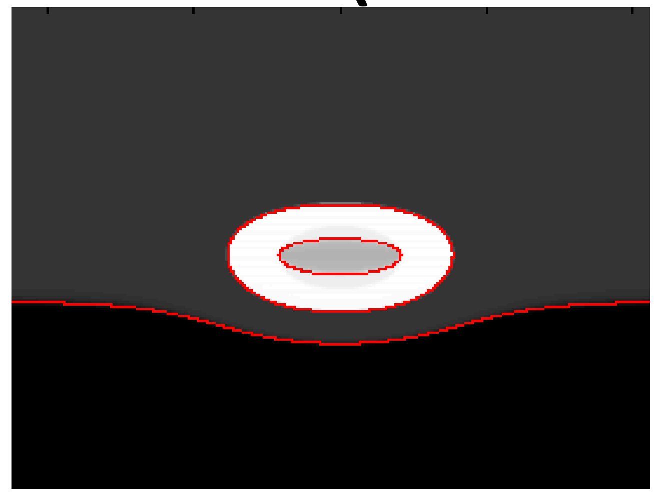
North-South velocity



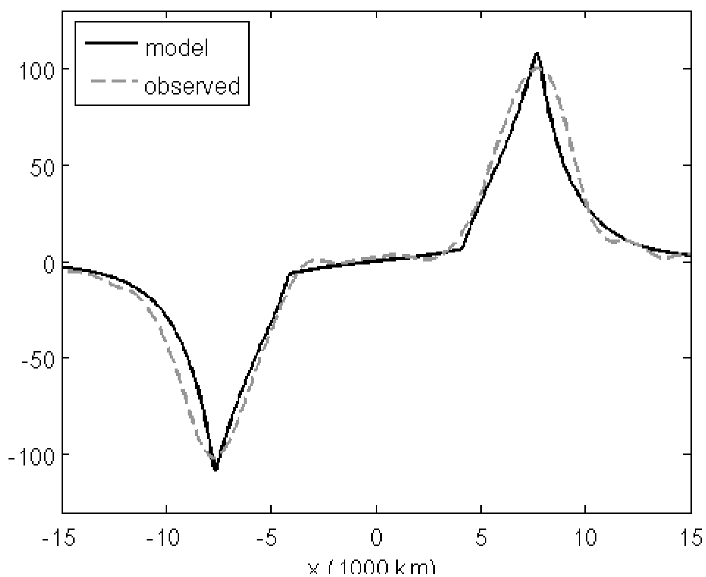
East-West velocity

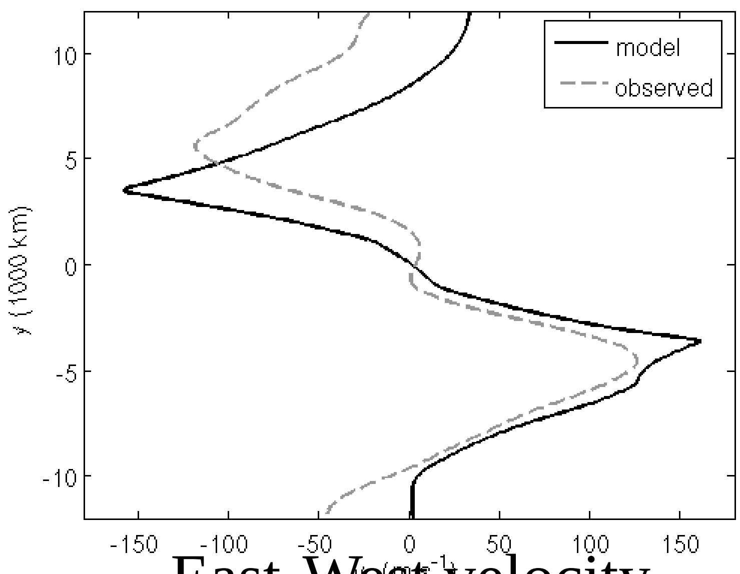
Inversion results for GRS (contd.)

- Best-fit model for N^{JET}=1, N^{VOR}=2.
- *L_r = 2300 km ± 100 km*
- RMS Error (model) = 23 ms^{-1}
- RMS Error (obs.) = 4.5 ms^{-1}



North-South velocity

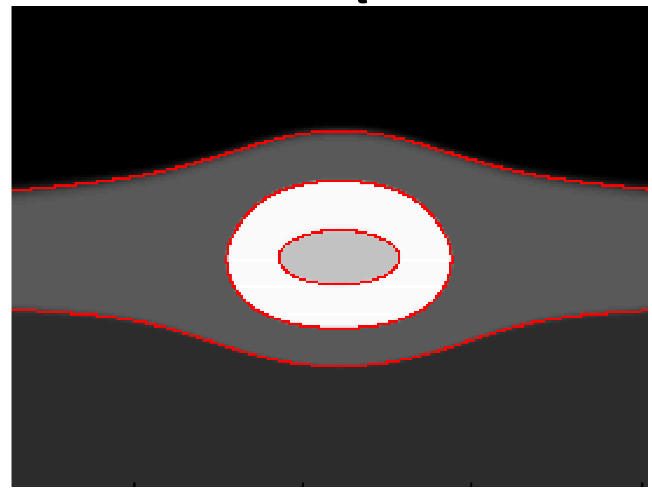




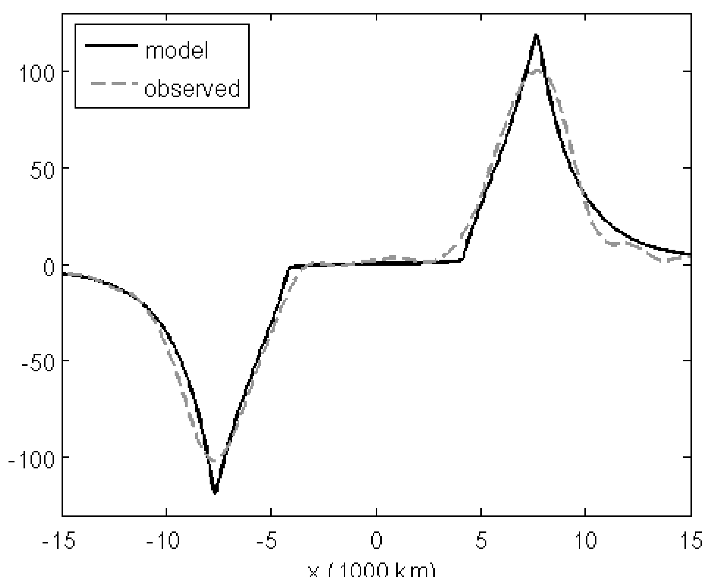
East-West velocity

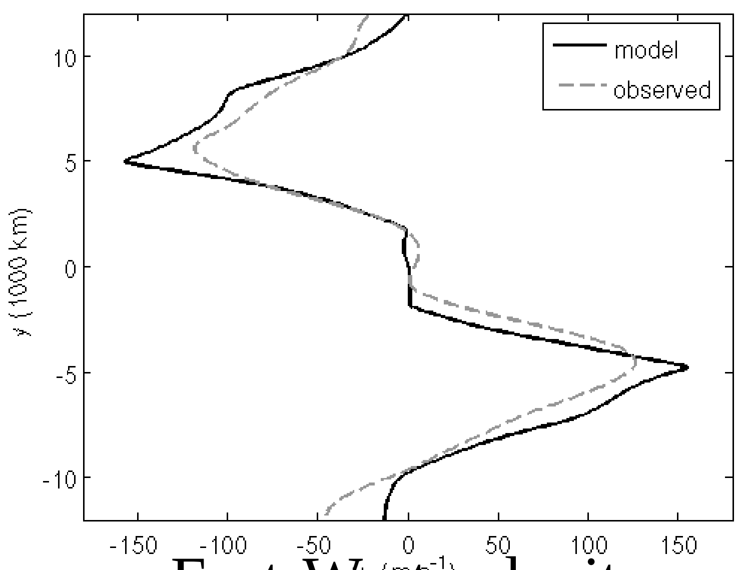
Inversion results for GRS (contd.)

- Best-fit model for $N^{JET}=2$, $N^{VOR}=2$.
- *L_r = 2300 km ± 100 km*
- RMS Error (model) = 14 ms^{-1}
- RMS Error (obs.) = 4.5 ms^{-1}

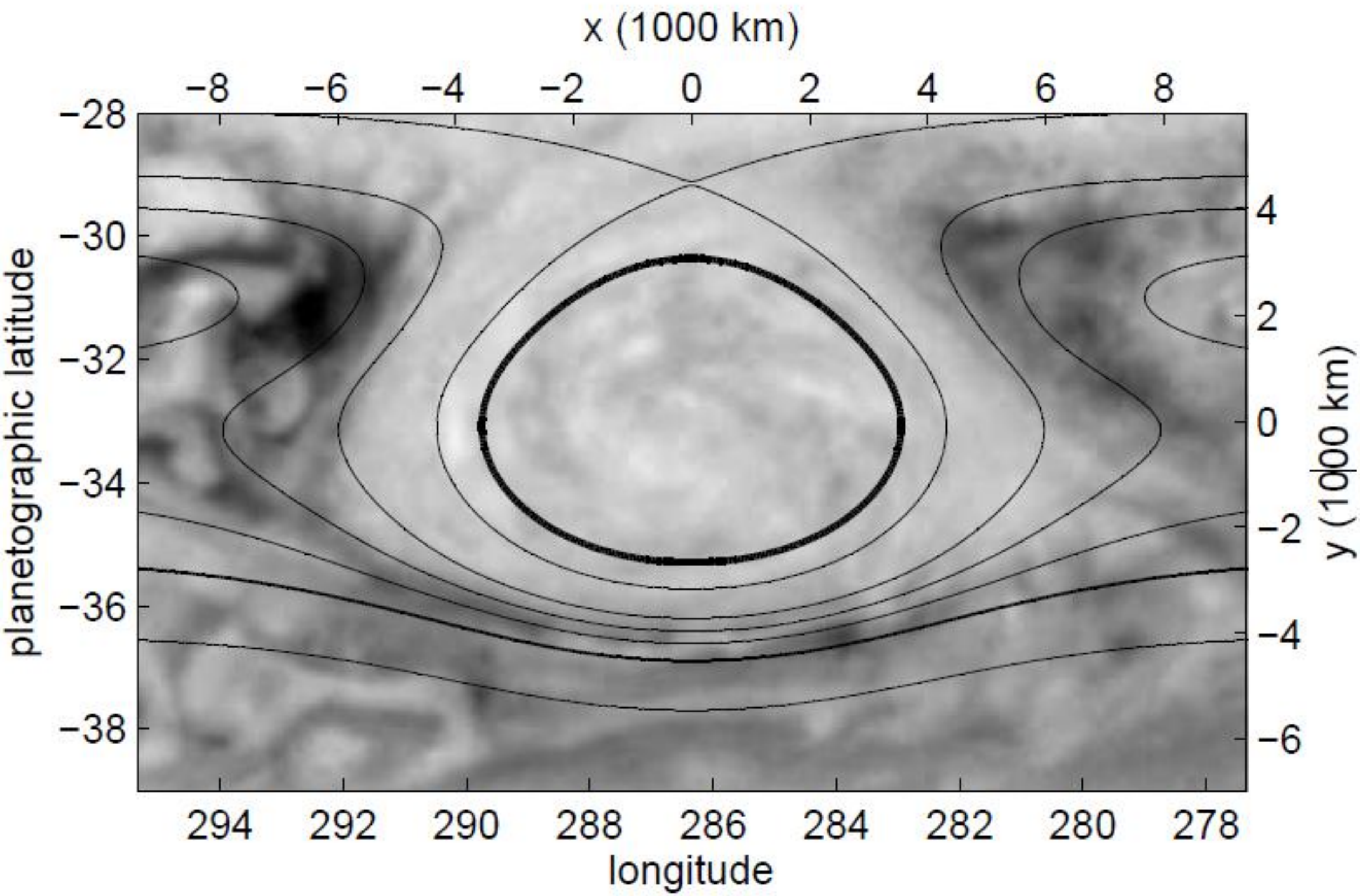


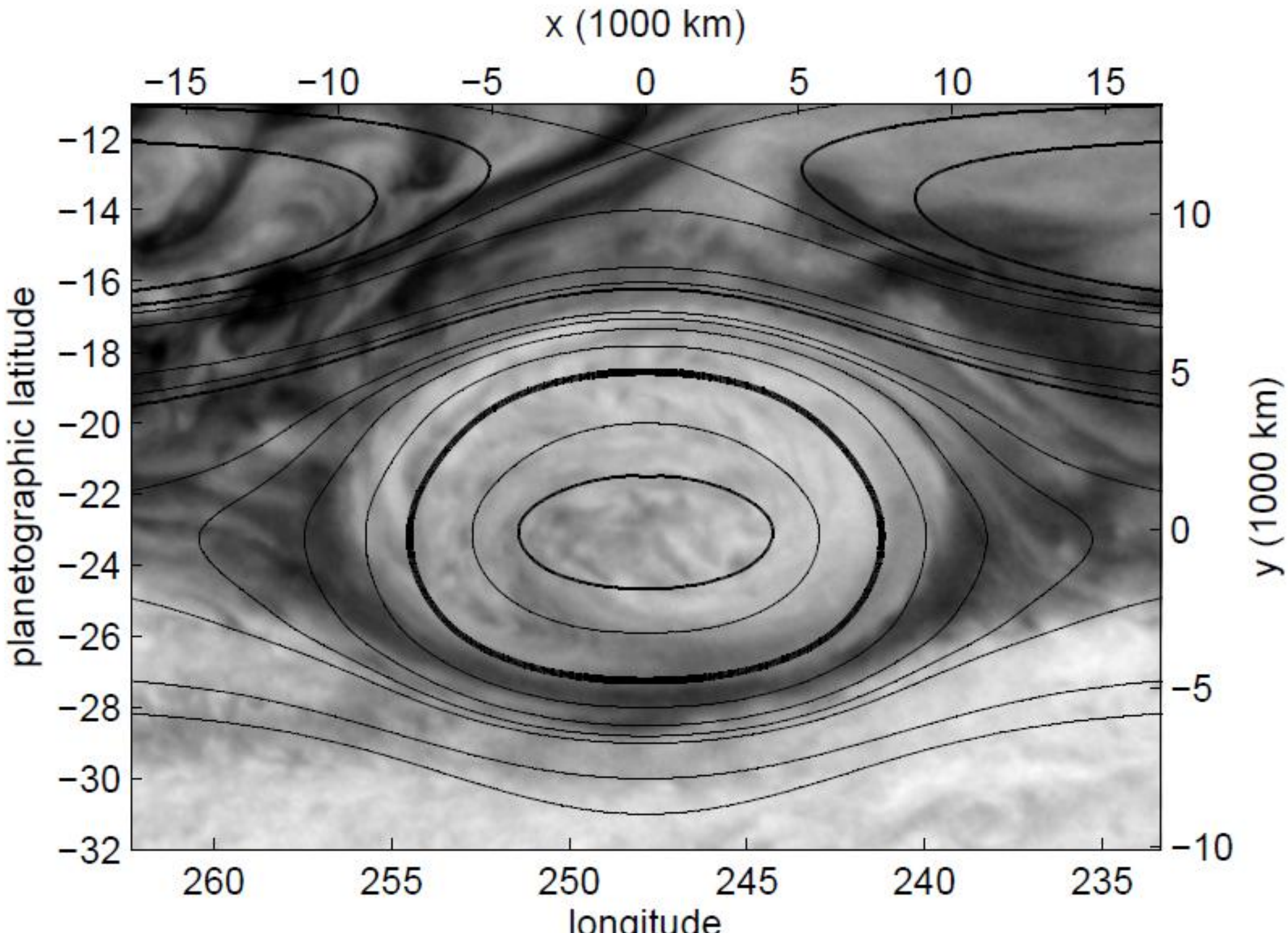
North-South velocity





East-West velocity


x (1000 km)
−8
−6
−4
−2
0
2
4
6
8
−28
−30
−32
−34
−36
−38
planetographic latitude
4
2
0
−2
−4
−6
y (1000 km)
294
292
290
288
286
284
282
280
278
longitude



x (1000 km)
−15
−10
−5
0
5
10
15
planetographic latitude
−12
−14
−16
−18
−20
−22
−24
−26
−28
−30
−32
y (1000 km)
10
5
0
−5
−10
260
255
250
245
240
235
longitude

Our Conclusion Based on HST:

There was a large (~20%) change in the global zonal flow at the latitude of the GRS between 1997 and 2006

The aspect ratio of the Potential Vorticity of vortex is (to 1st order) a fn. of | Potential Vorticity | / | local shear |

Moore & Saffman, Aircraft Wake Vortices, 1971; PSM, Ann. Rev. Astron. & Atstrophys., 1993

The Velocity of the High Speed Collar is (to 1st order) a fn. of | Potential Vorticity | * (Deformation Radius)

The collar velocity's change since 1979 has been less than its uncertainty (4%); either the P.V. is unchanged or the D.R. has changed, a change in D.R. of 5% corresponds to ~4°K.

GRS has become rounder

- From observations:

	Galileo (1996)	Hubble (2006)
$(D_x)_1$	18300±100 km	15400±200 km
$(D_x)_2$	11000±100 km	7000±200 km
$(D_y)_1$	9600±100 km	10200±200 km
V_y^{MAX}	102±3 m s^{-1}	102±5 m s^{-1}

- Changed:

$$\Delta(D_x)_1/(\bar{D}_x)_1 = [-16 \pm 1]\%$$
$$\Delta(D_x)_2/(\bar{D}_x)_2 = [-36 \pm 2]\%$$
$$\Delta(D_y)_1/(\bar{D}_y)_1 = [6 \pm 3]\%$$

- May or may not have changed:

$$\Delta V_y^{MAX}/\bar{V}_y^{MAX} = [0 \pm 6]\%$$

Rounder GRS a symptom of *zonal* Change on Jupiter?

Phillips Effect

- General Mixing process
- Applicable to any quantity that is advectively conserved
- Originally, applied to the salt density in the upper layers of the ocean
- Homegenization and Staircasing
  - interfaces are barriers to mixing
  - stable configurations
- Applied to zonal flows in ocean and atmosphere

SPECIAL
Jets and Annular Structures in Geophysical Fluids
COLLECTION

JOURNAL OF THE ATMOSPHERIC SCIENCES

Forced-Dissipative Shallow-Water Turbulence on the Sphere and the Atmospheric Circulation of the Giant Planets

R. K. SCOTT AND L. M. POLVANI

Multiple Jets as PV Staircases: The Phillips Effect and the Resilience of Eddy-Transport Barriers

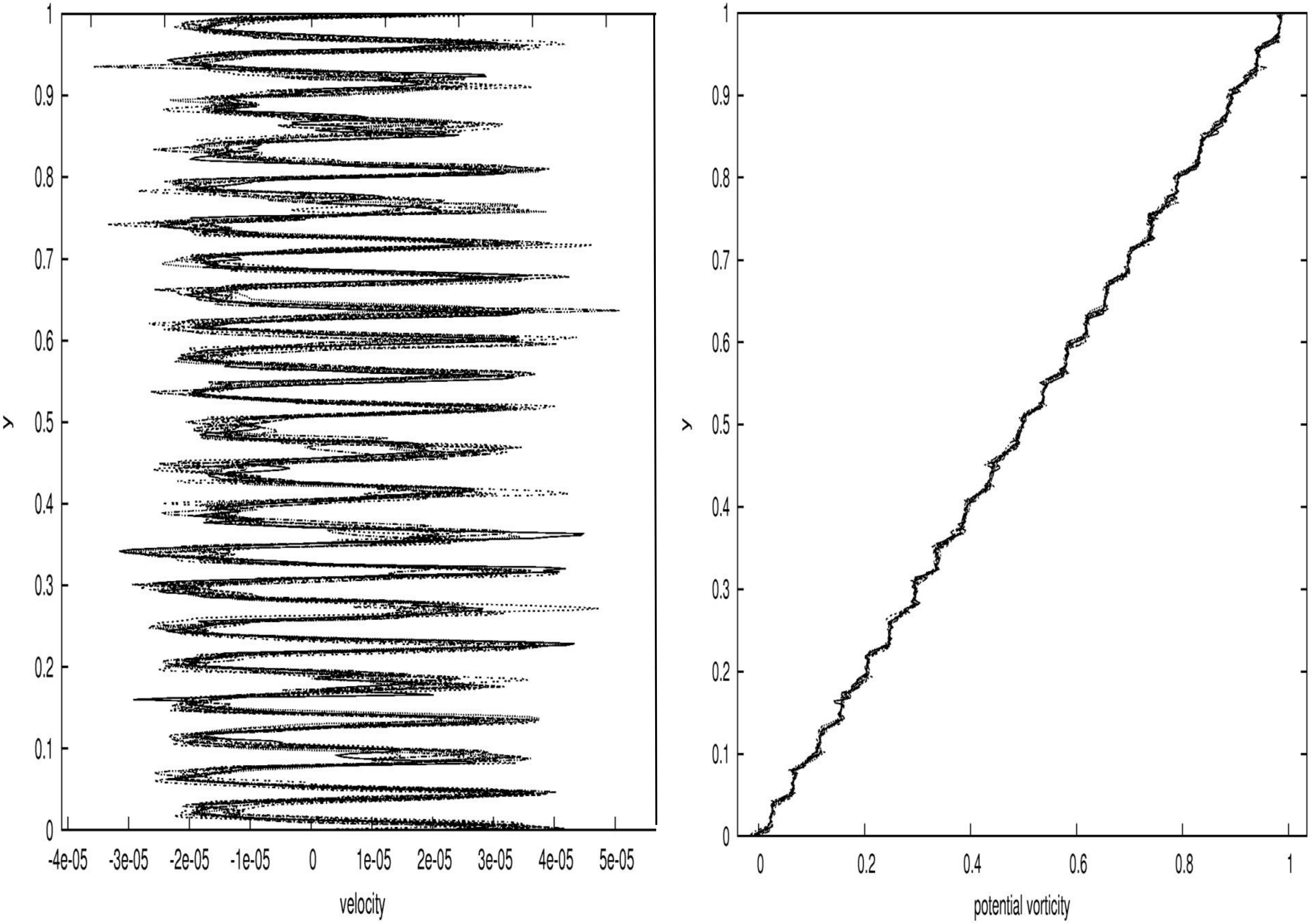
D. G. DRITSCHEL AND M. E. MCINTYRE

Formation of Jets by Baroclinic Instability on Gas Planet Atmospheres

YOHAI KASPI AND GLENN R. FLIERL

A Barotropic Model of the Angular Momentum–Conserving Potential Vorticity Staircase in Spherical Geometry

TIMOTHY J. DUNKERTON AND RICHARD K. SCOTT

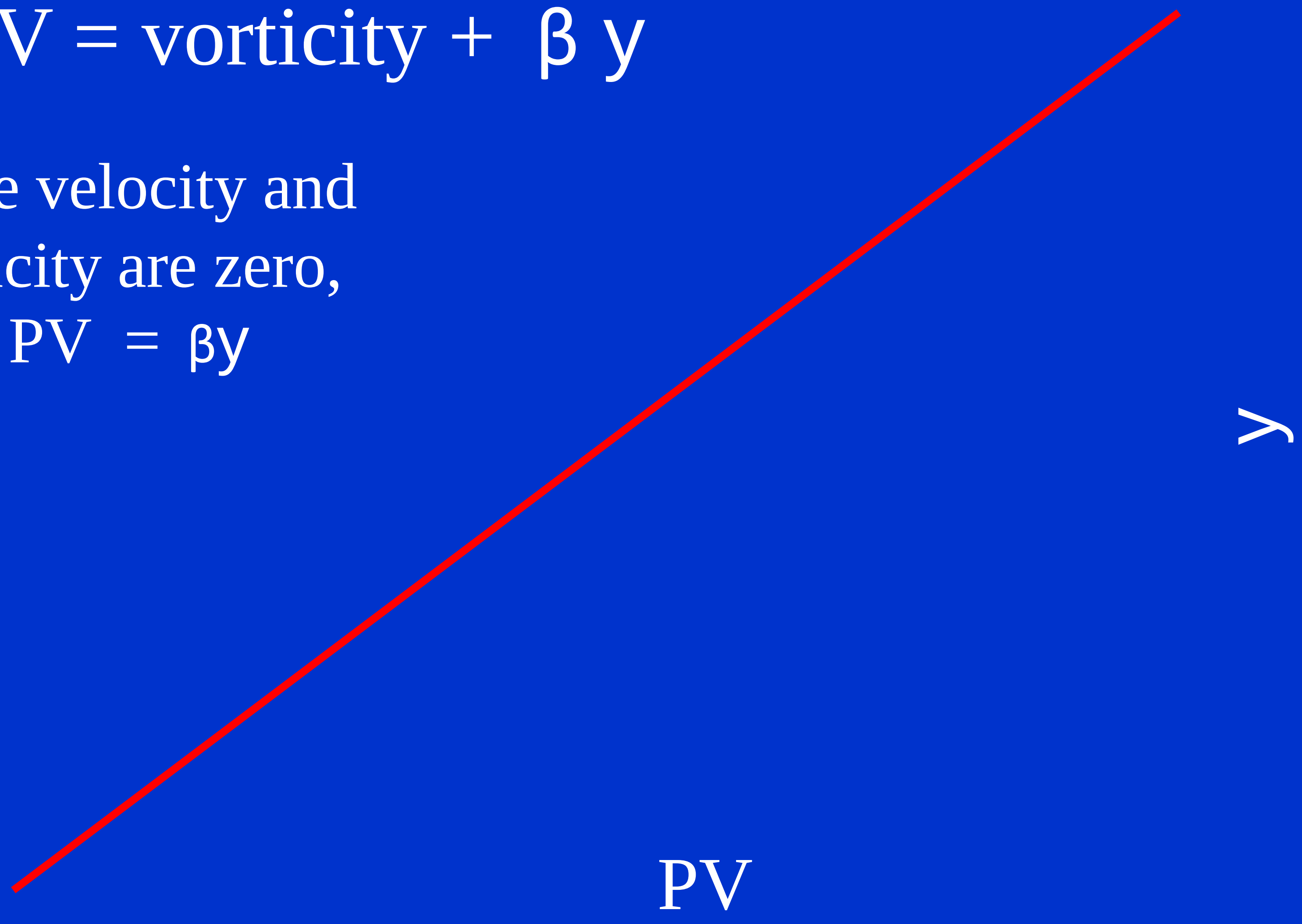


y
velocity
-4e-05
-3e-05
-2e-05
-1e-05
0
1e-05
2e-05
3e-05
4e-05
5e-05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
y
potential vorticity
0
0.2
0.4
0.6
0.8
1

Monotonic Staircases

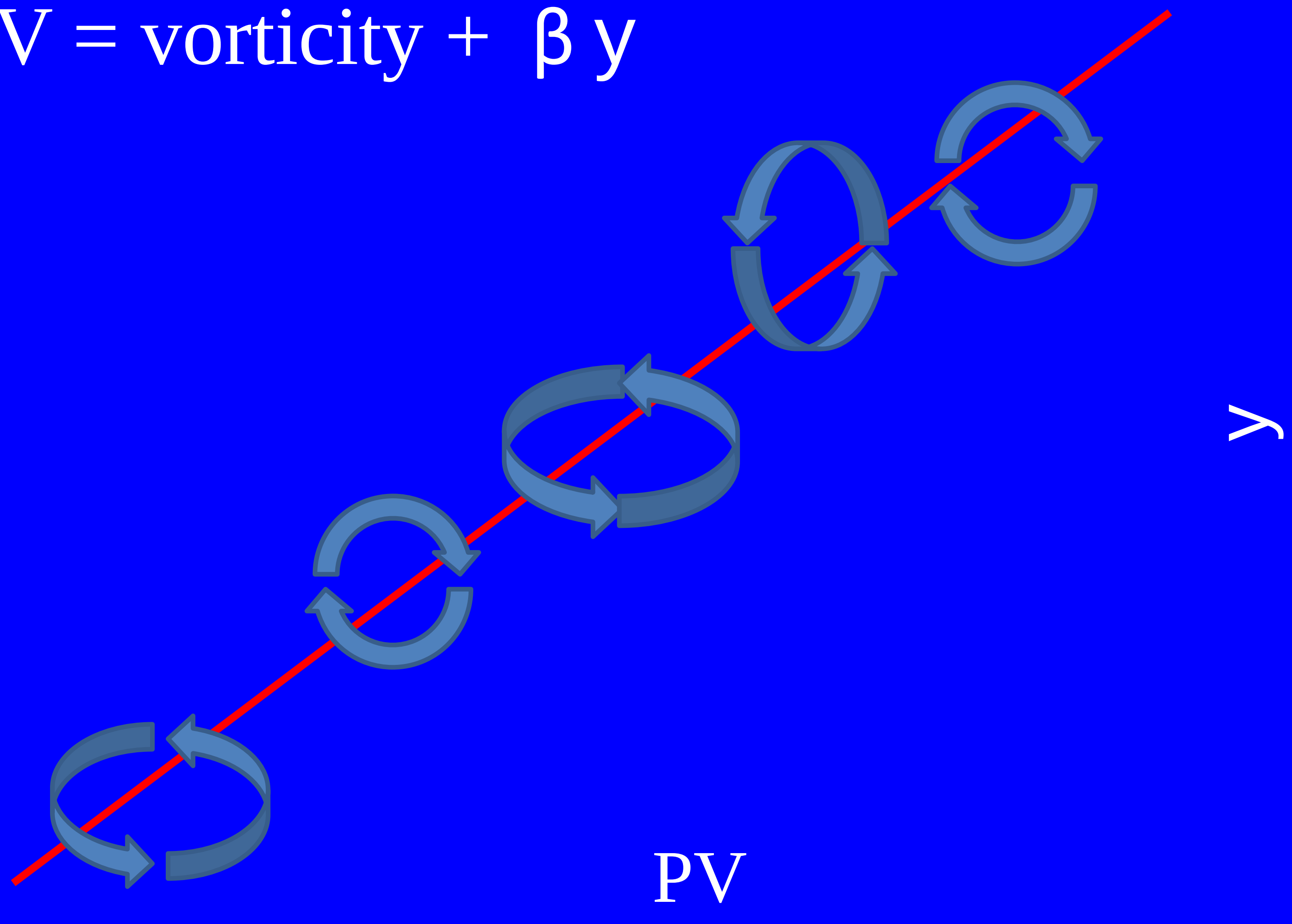
$$PV = \text{vorticity} + \beta y$$

If the velocity and vorticity are zero, then $PV = \beta y$

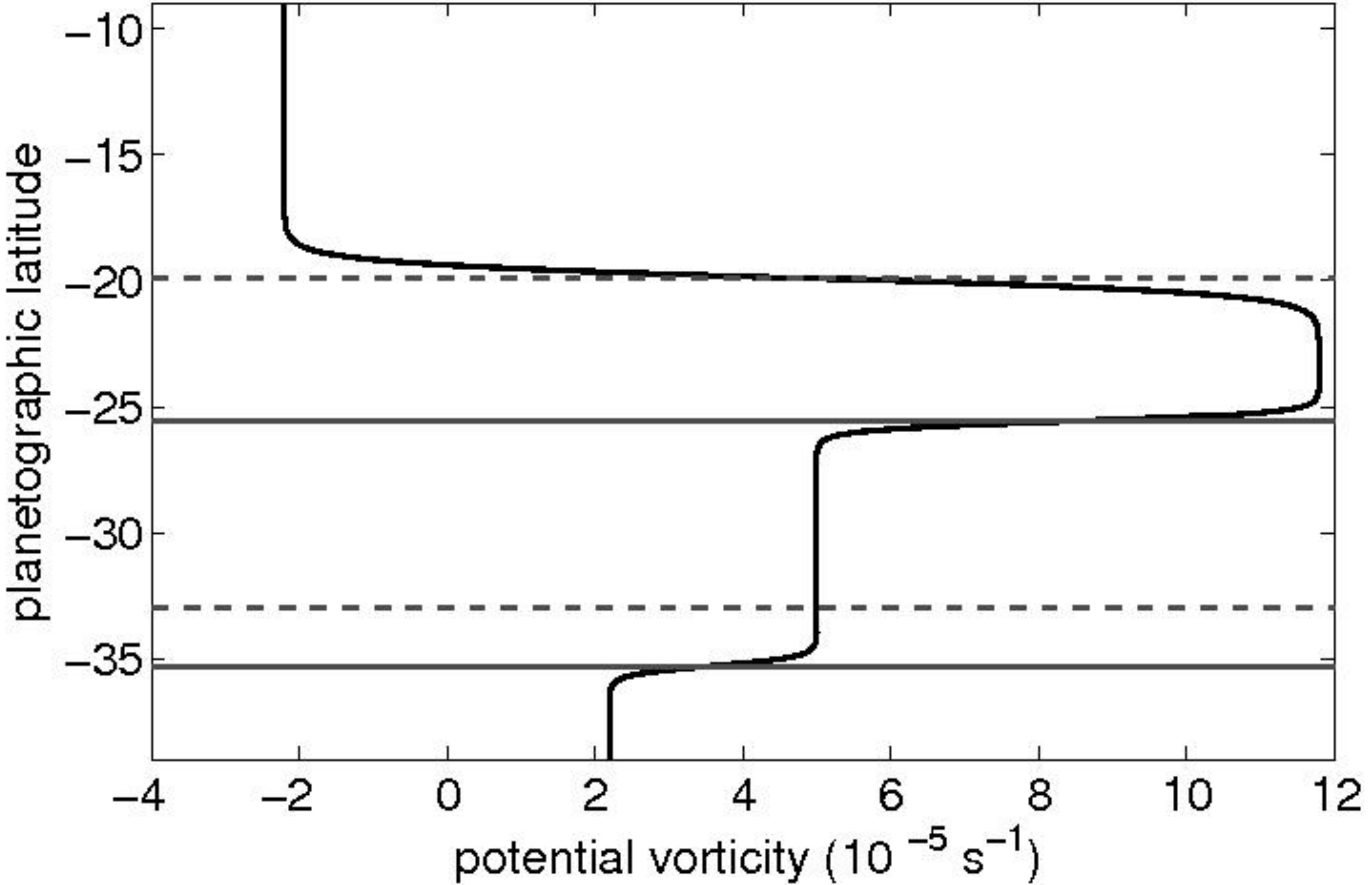


Monotonic Staircase

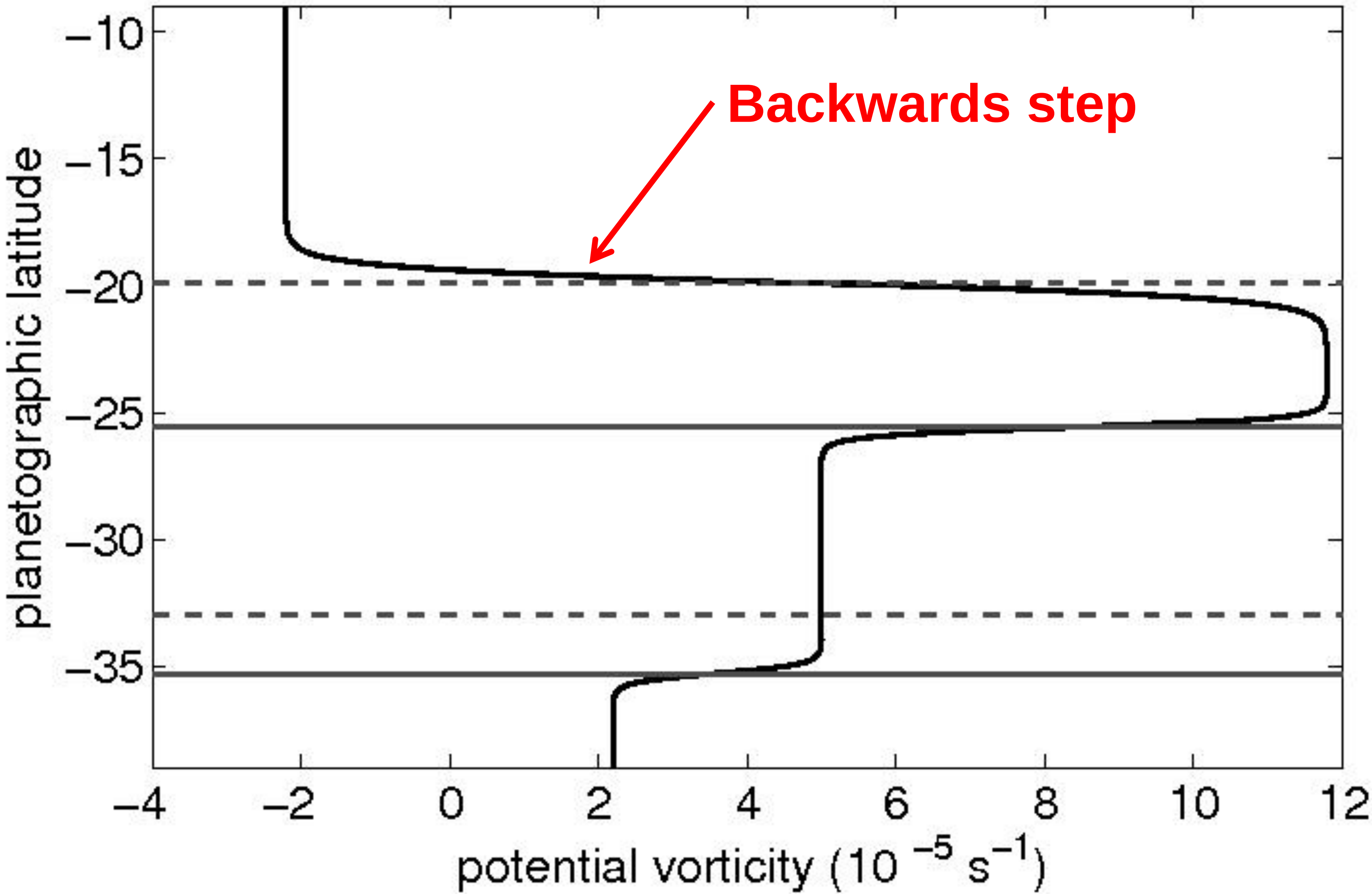
PV = vorticity + β y

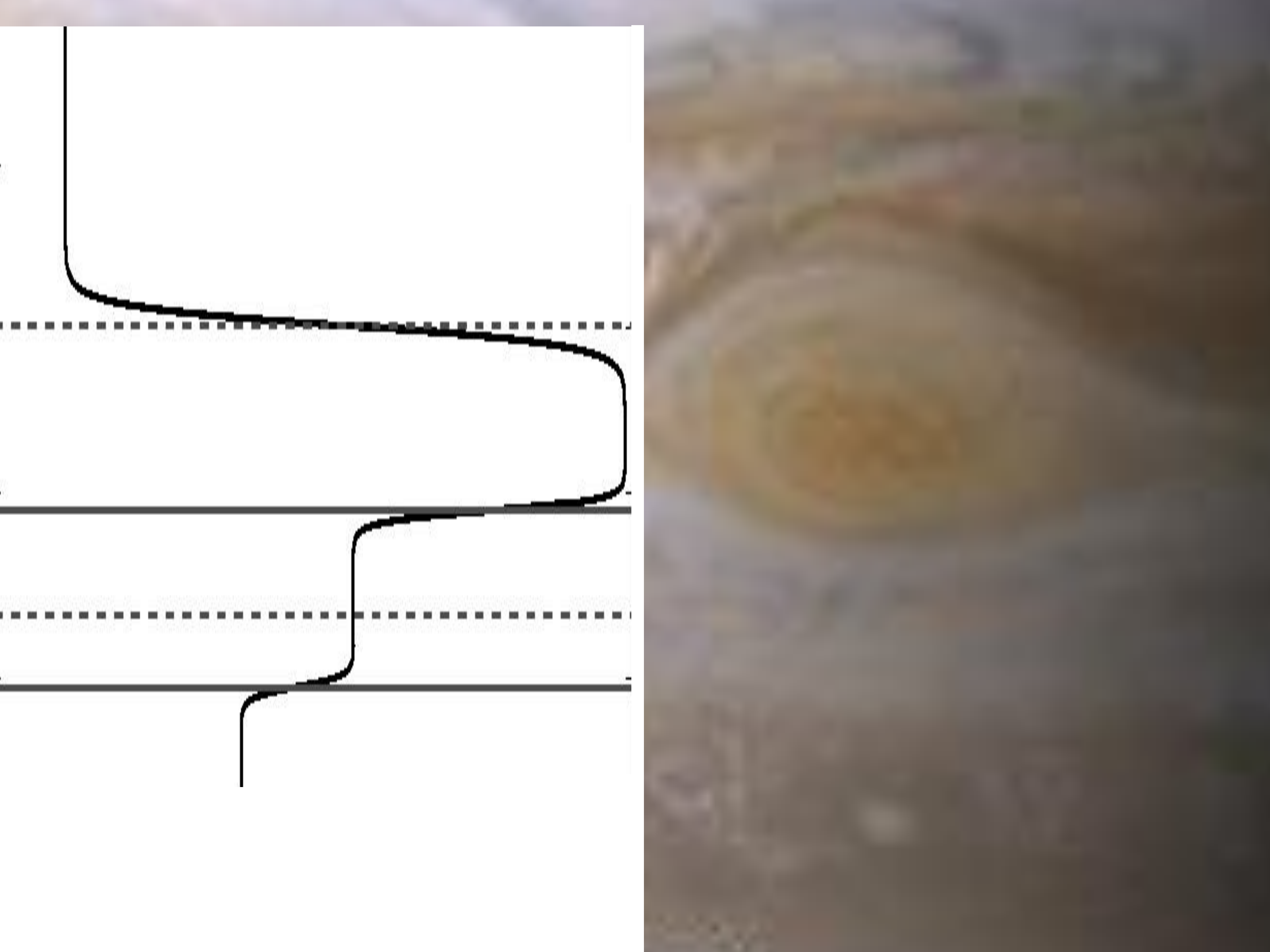


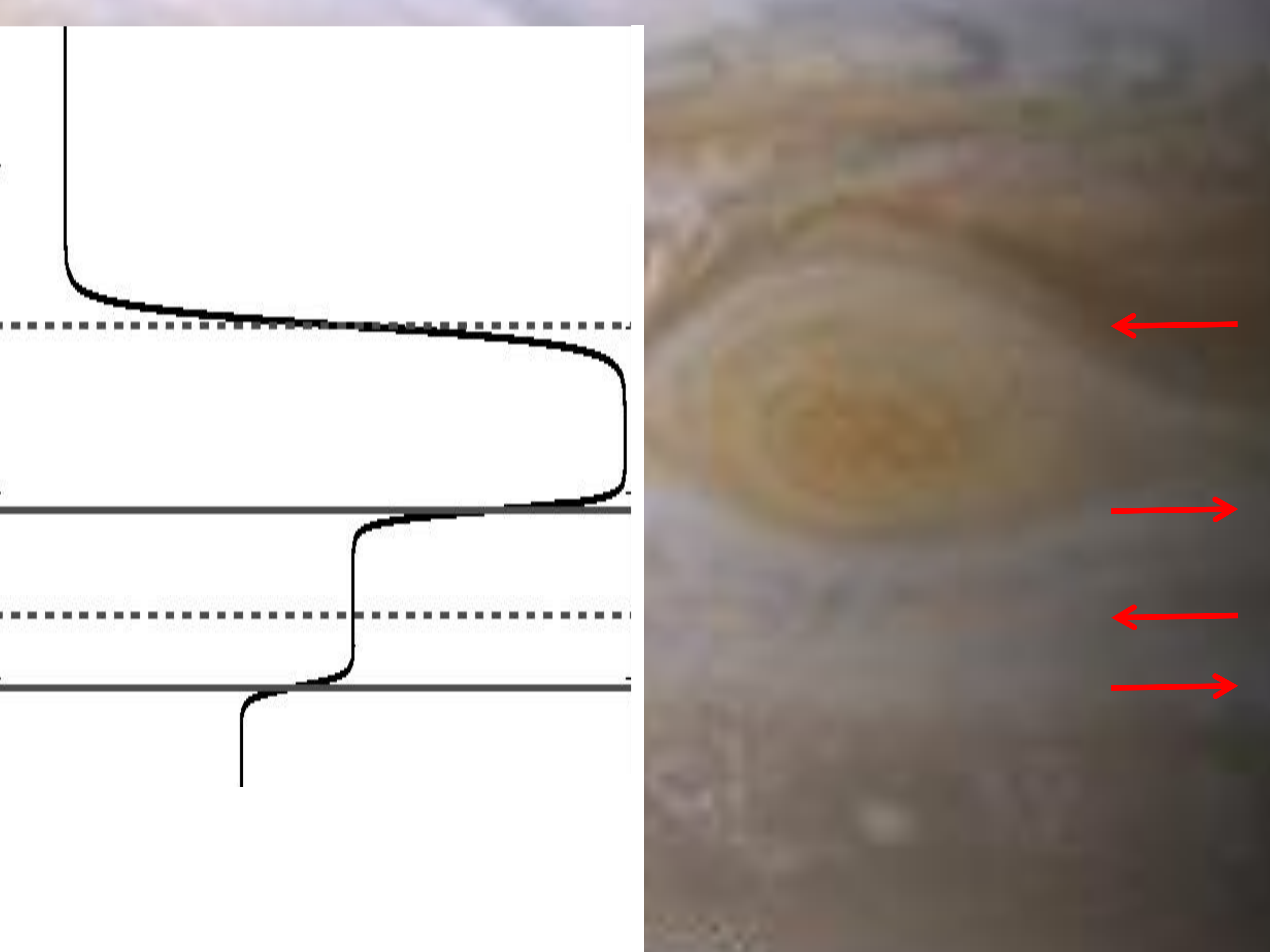
Potential Vorticity as Function of Latitude



Potential Vorticity as Function of Latitude





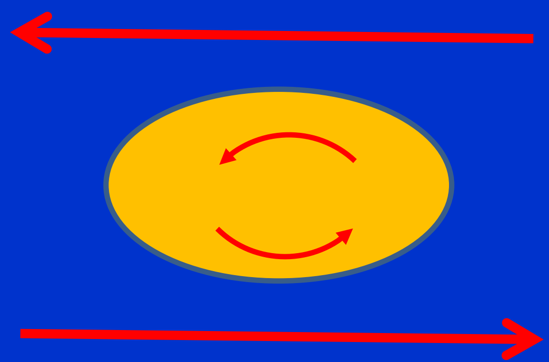


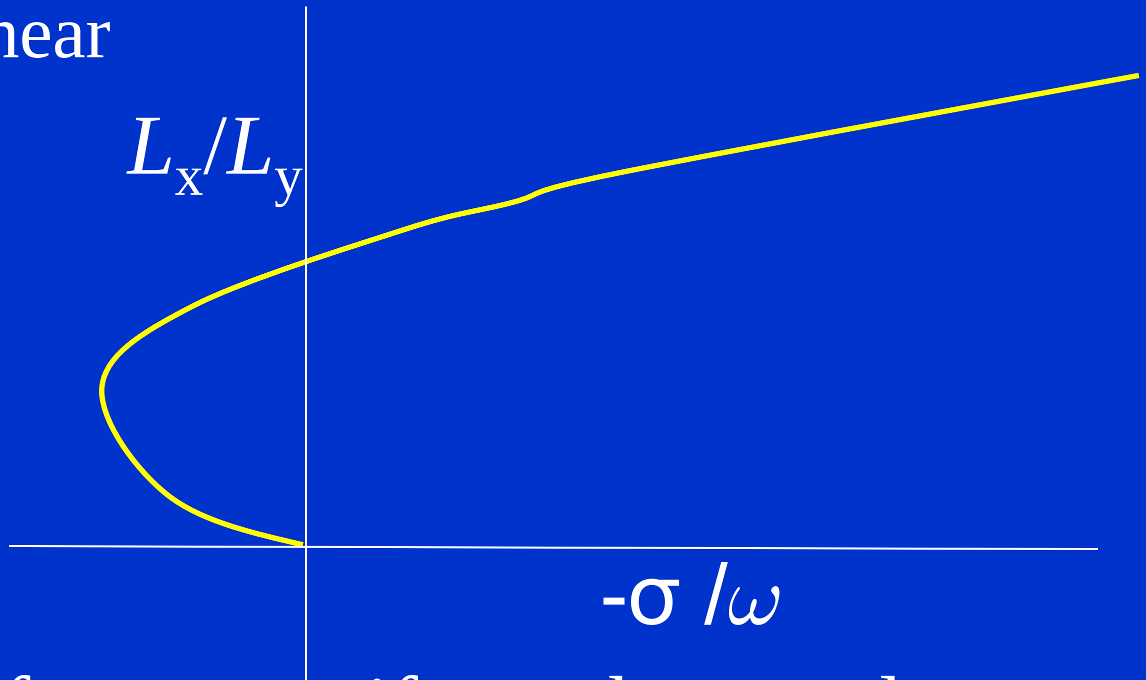
Not very satisfying or convincing to claim that "best-fit" solution to an inverse problem with several million degrees of freedom is a zonal velocity is that is "non-staircased"

Fortunately, there are two additional, physics-based, ways to show that there must be a large "backwards" Potential Vorticity Jump

Aspect Ratio L_x/L_y of a Vortex

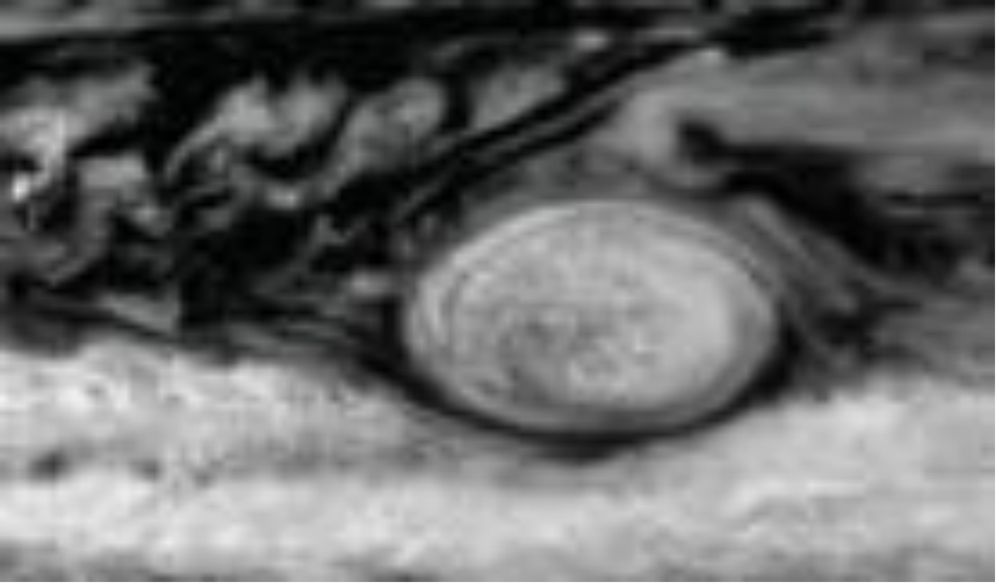
Moore and Saffman examined the equilibrium shape of a patch of uniform vorticity ω embedded in a flow with uniform shear

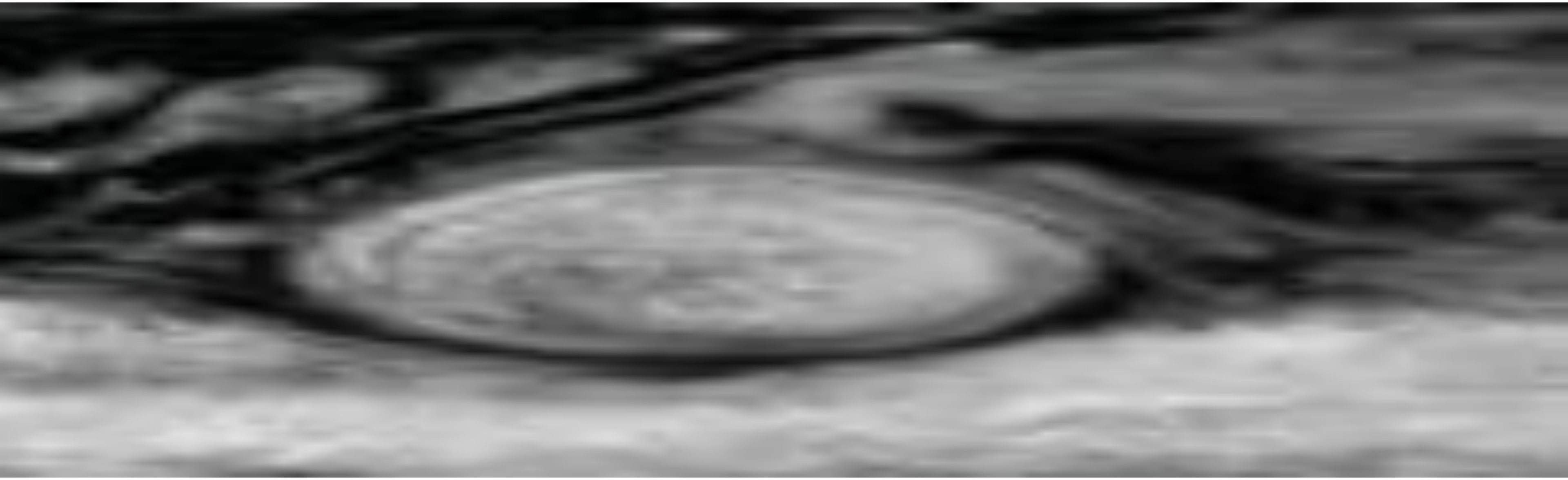


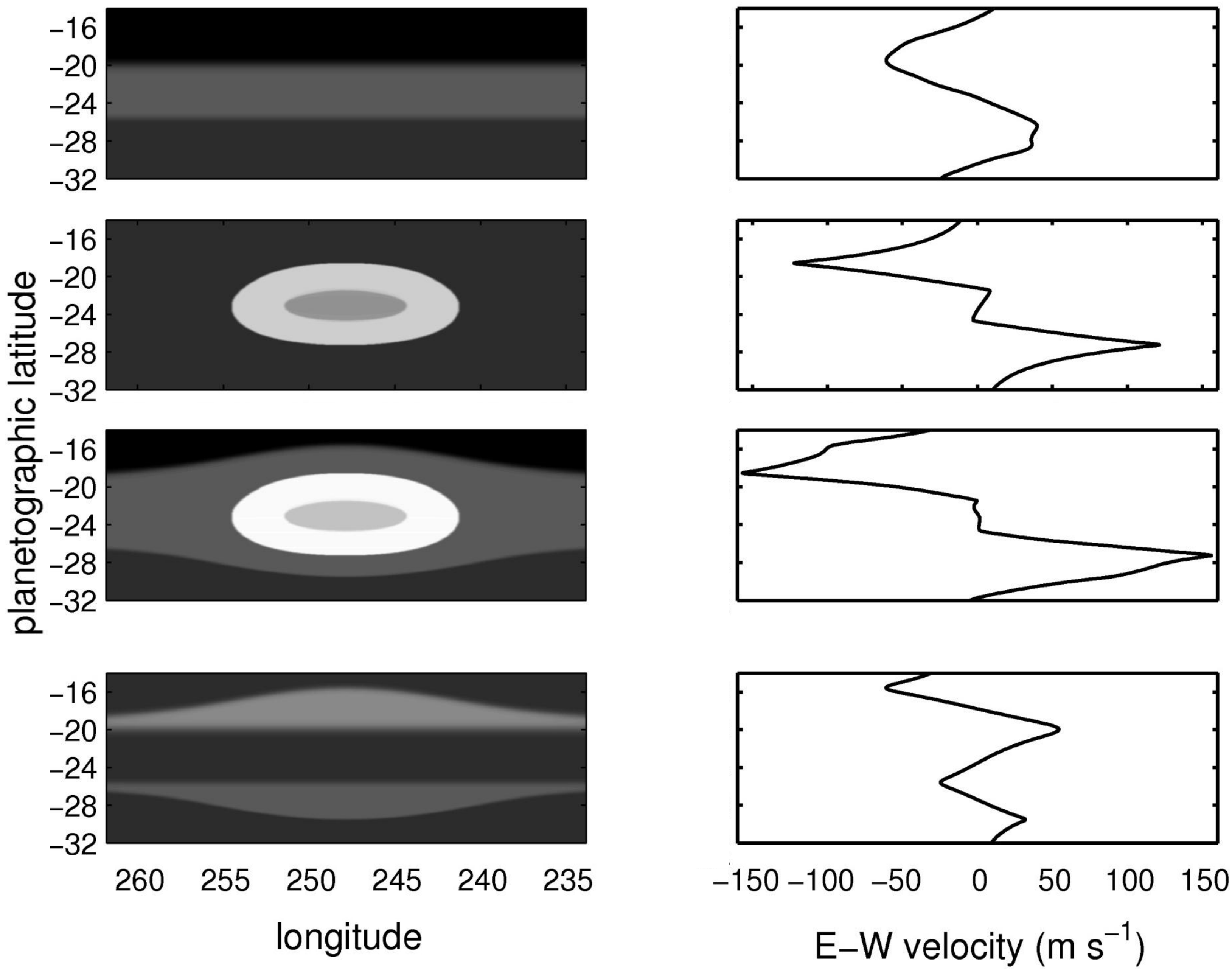


Robust relationship for non-uniform shear and non-uniform vortices

Replace ω with PV (also weak function of L_xL_y/L_r^2)






planetographic latitude
−16
−20
−24
−28
−32
260
255
250
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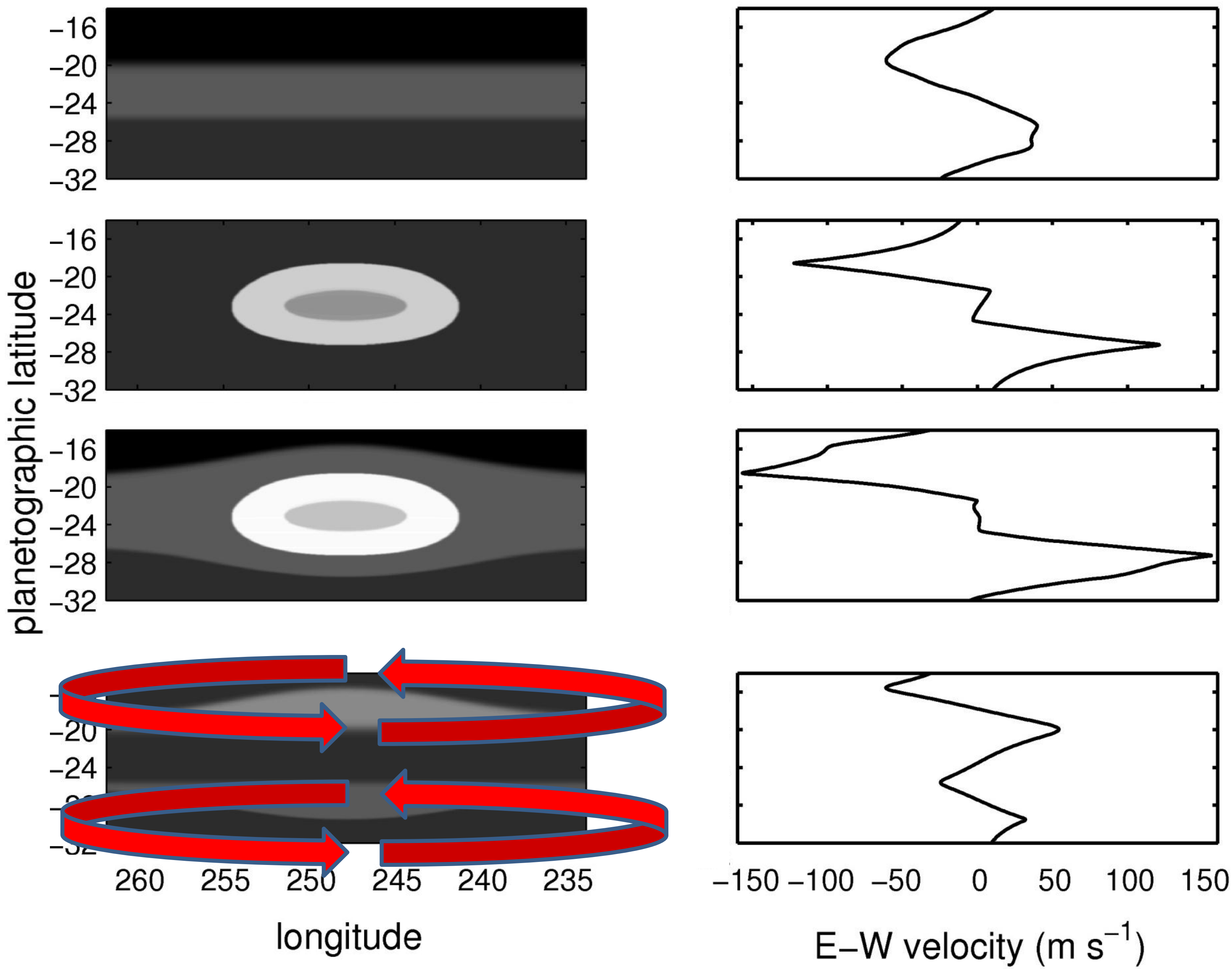
240
235
longitude
−150
−100
−50
0
50
100
150
E−W velocity (m s−1)



planetographic latitude
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longitude
−150
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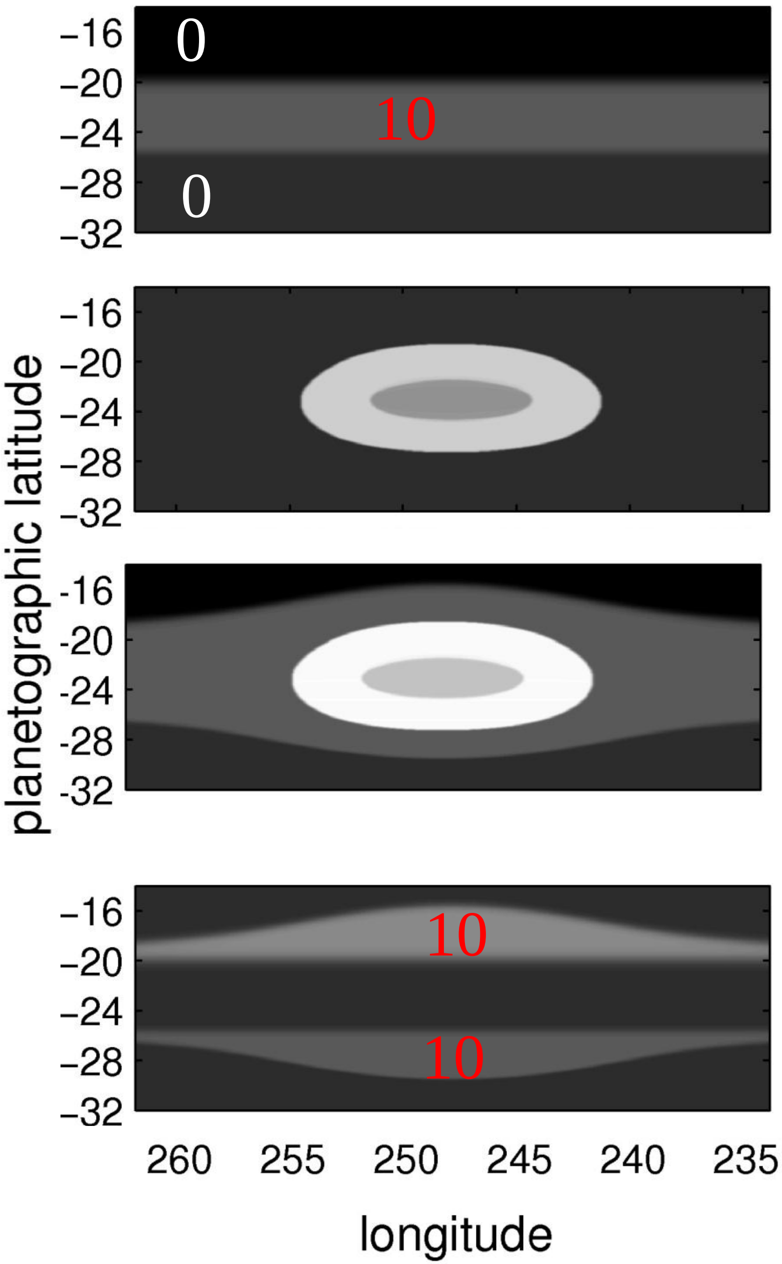
−50
0
50
100
150
E−W velocity (m s^{-1})



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planetographic latitude
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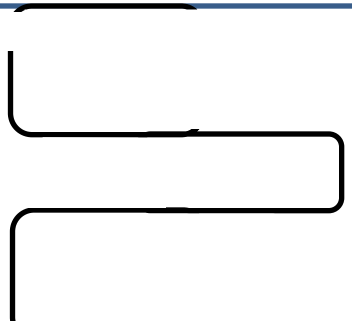
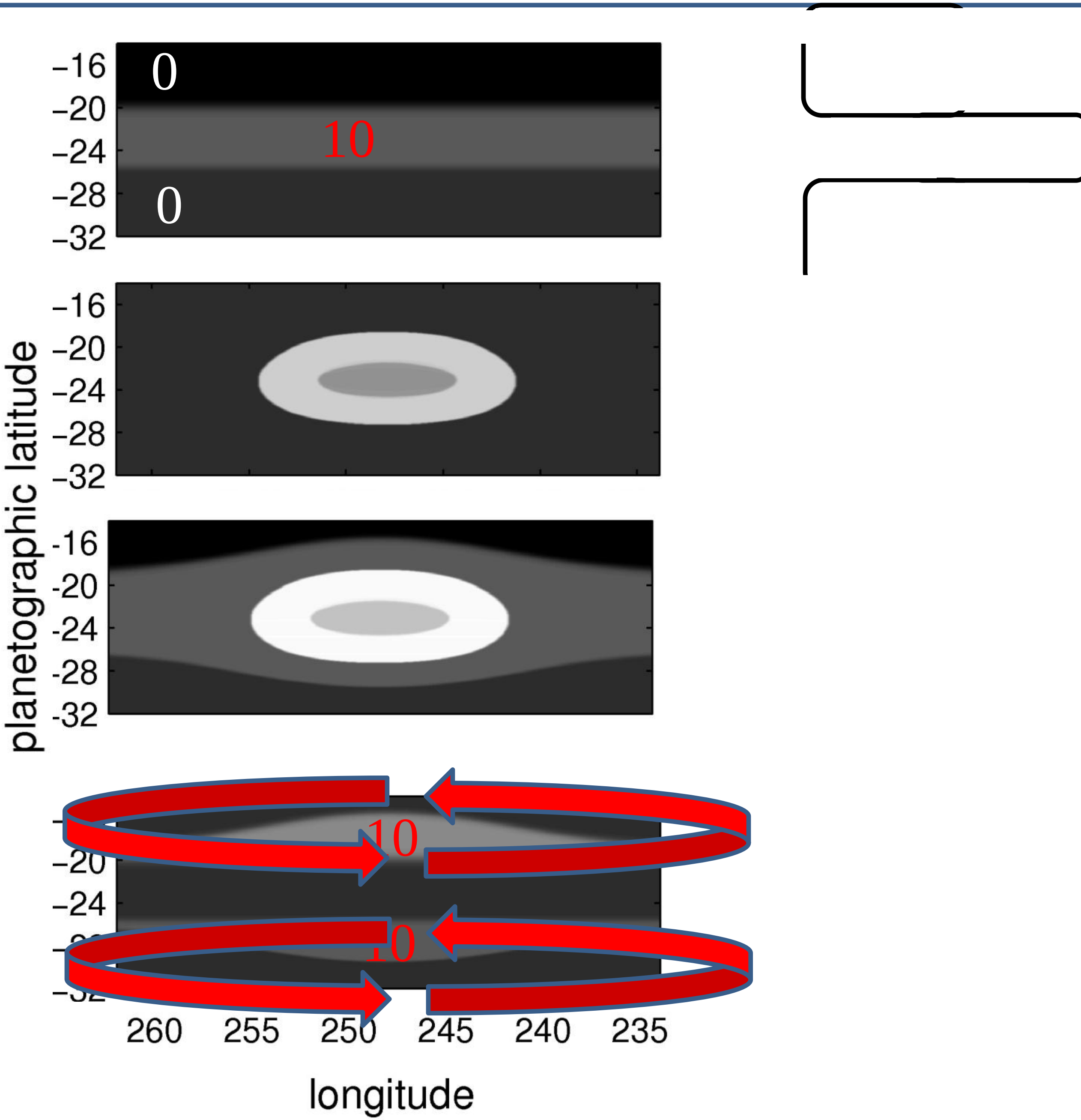
longitude

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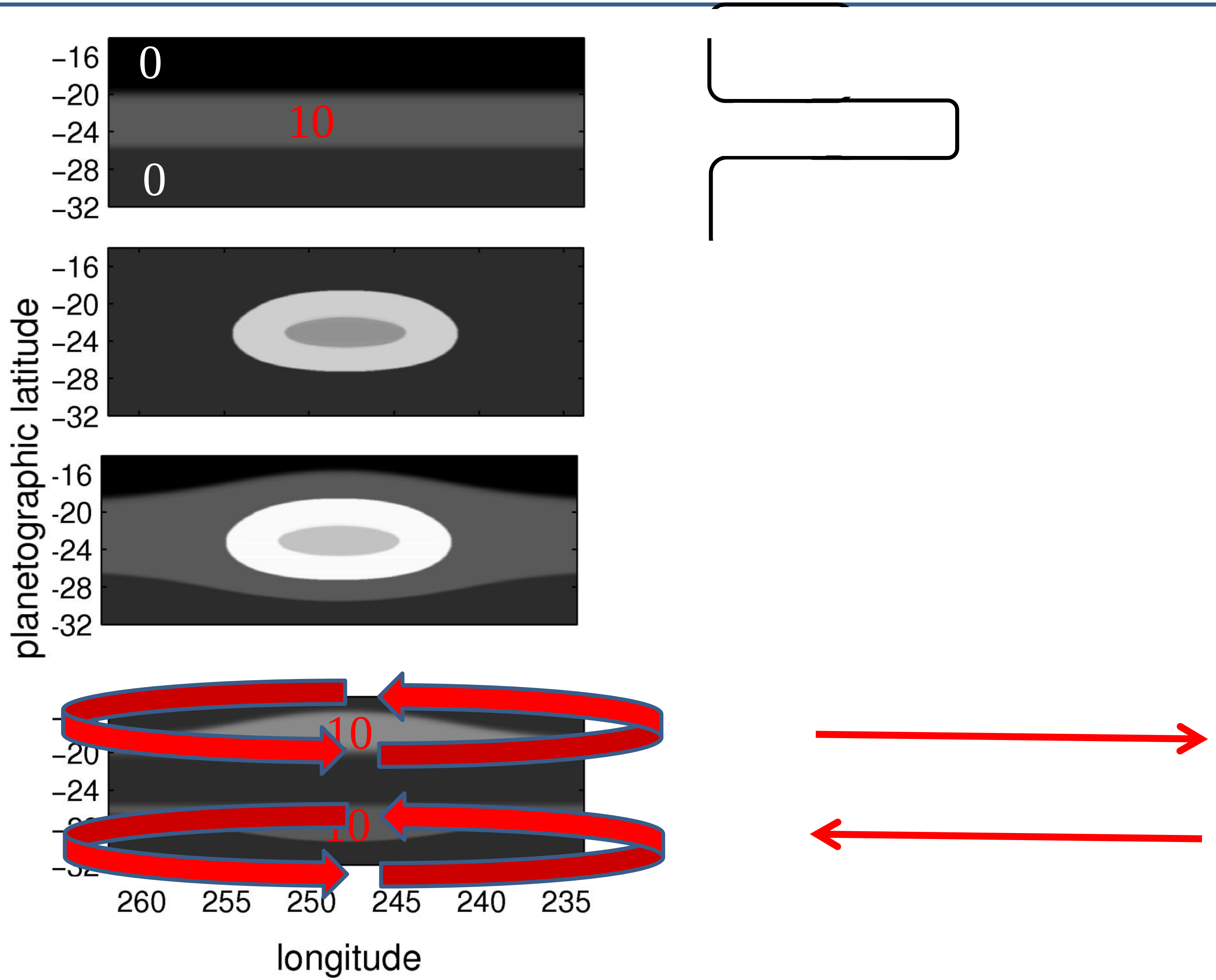

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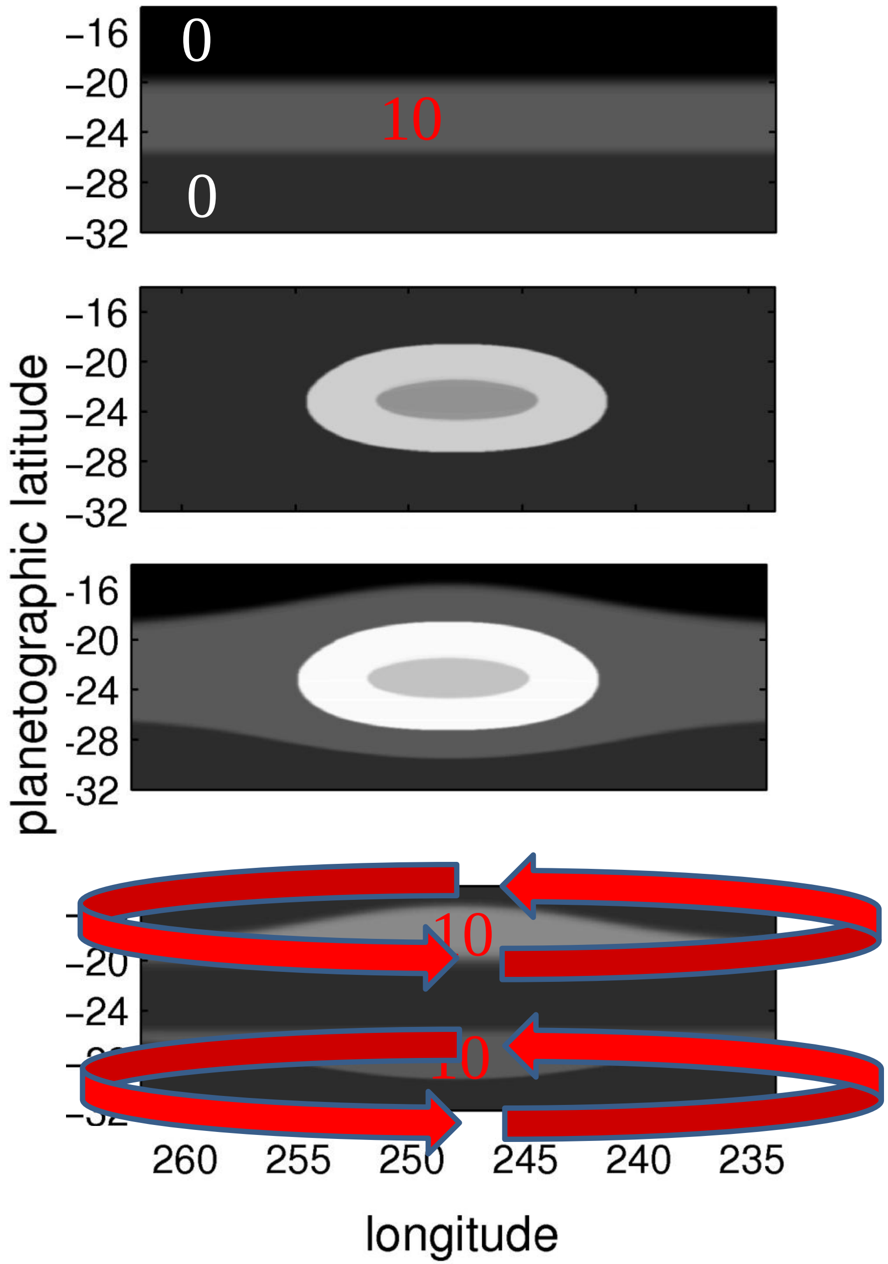
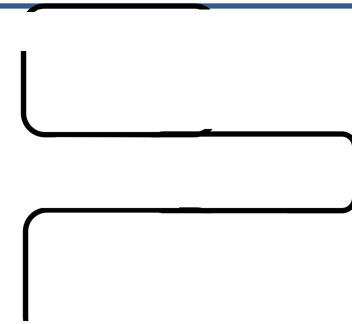
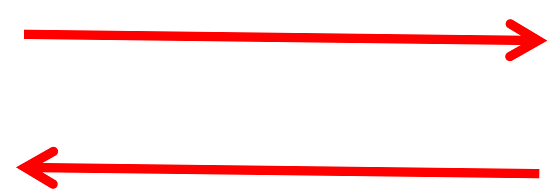
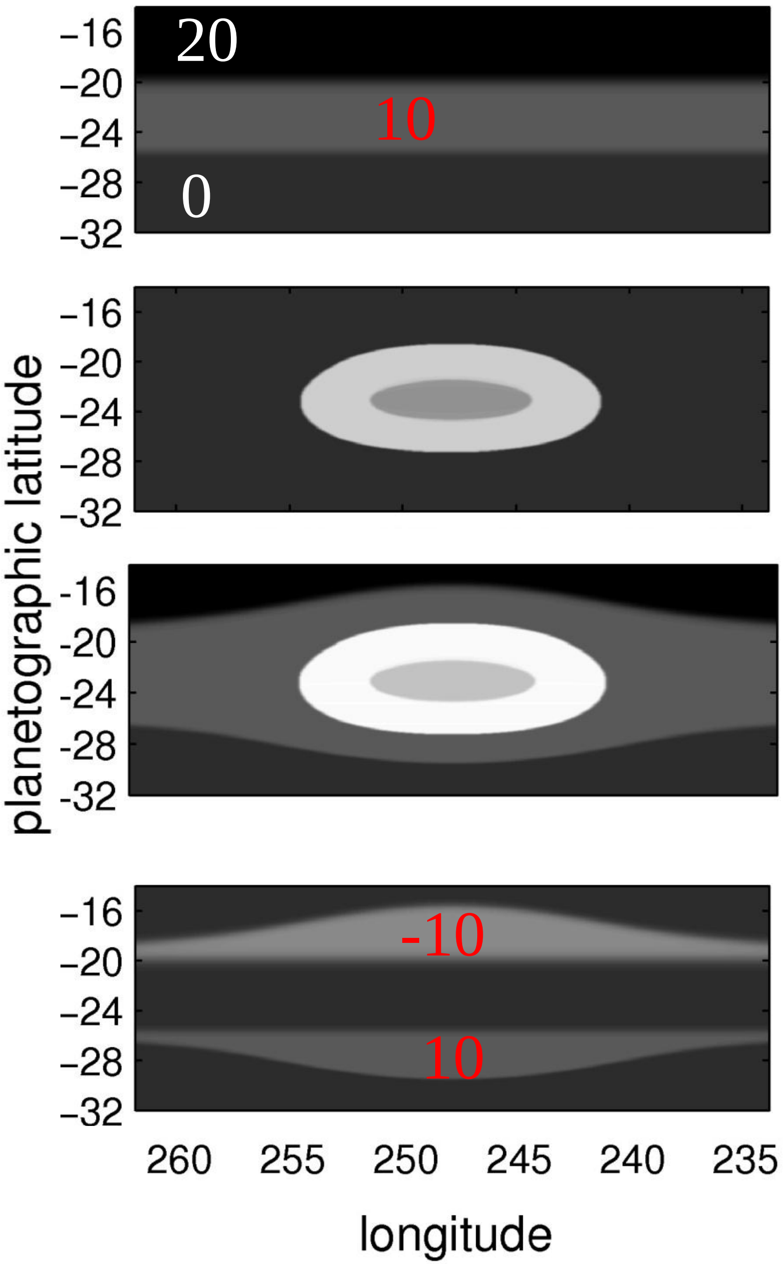
longitude





The induced shear from each interface is proportional to the strength of the discontinuity in PV at the interface




20
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planetographic latitude
-16
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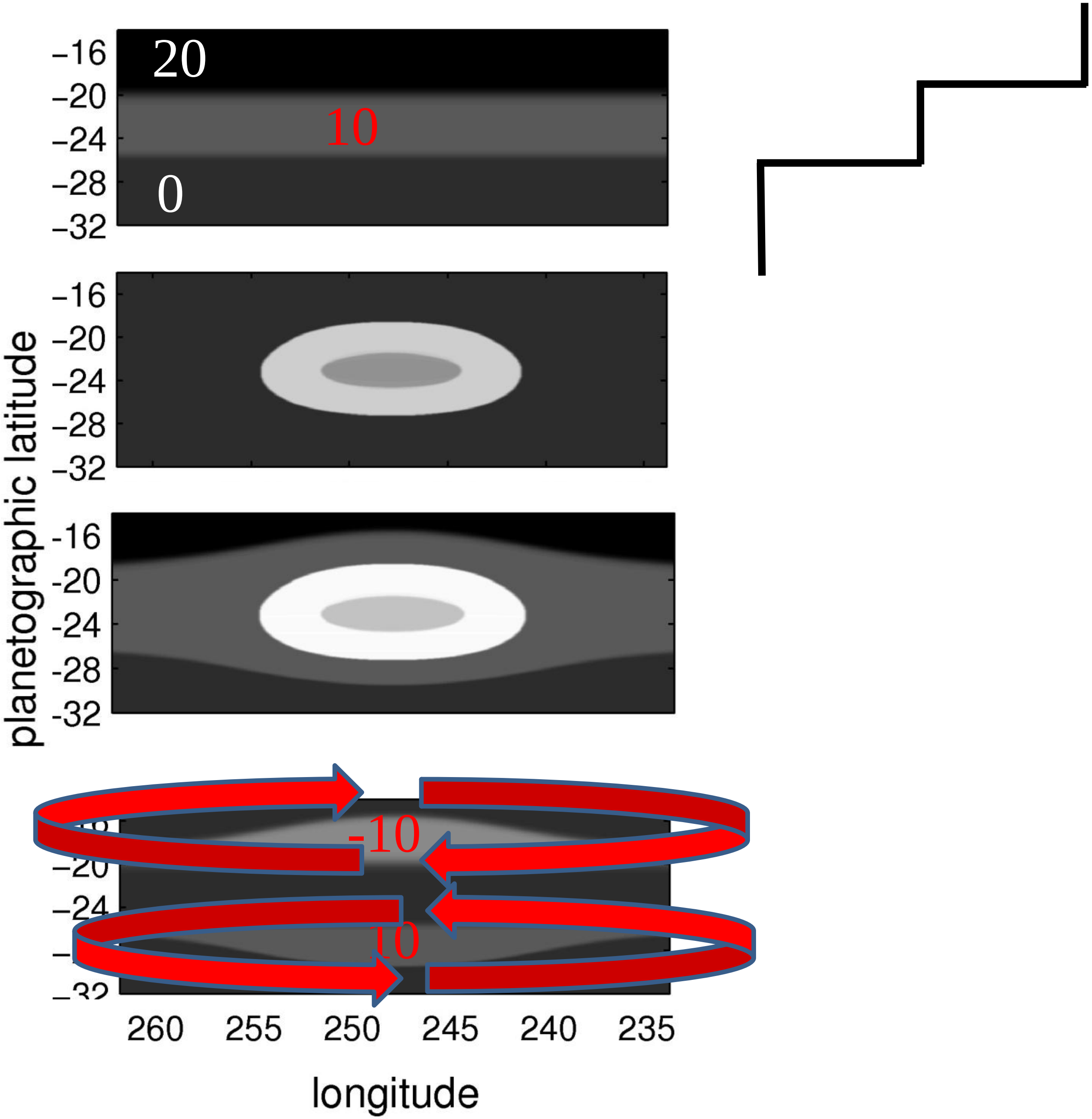
longitude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planetographic latitude
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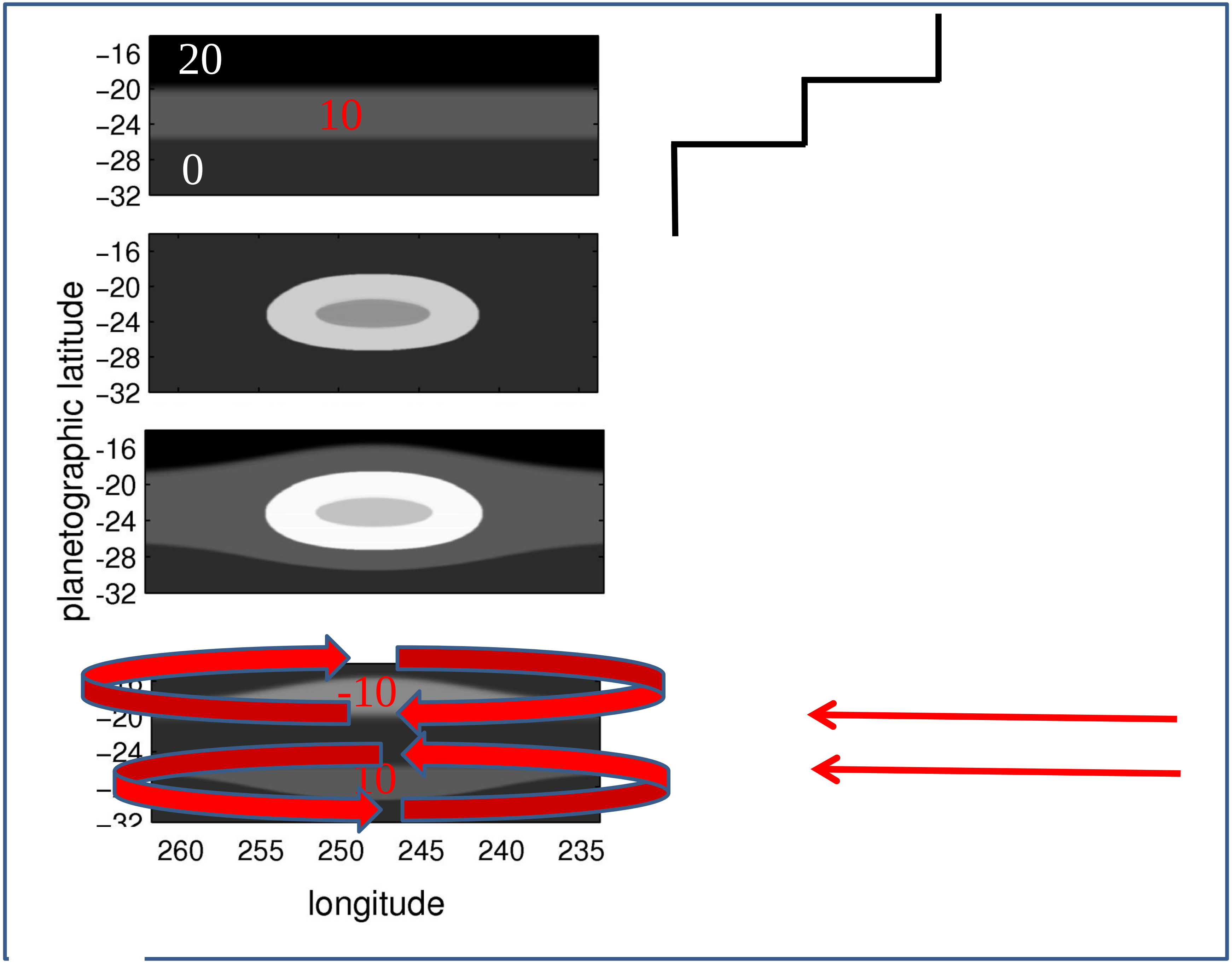
longitude



20
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planetographic latitude
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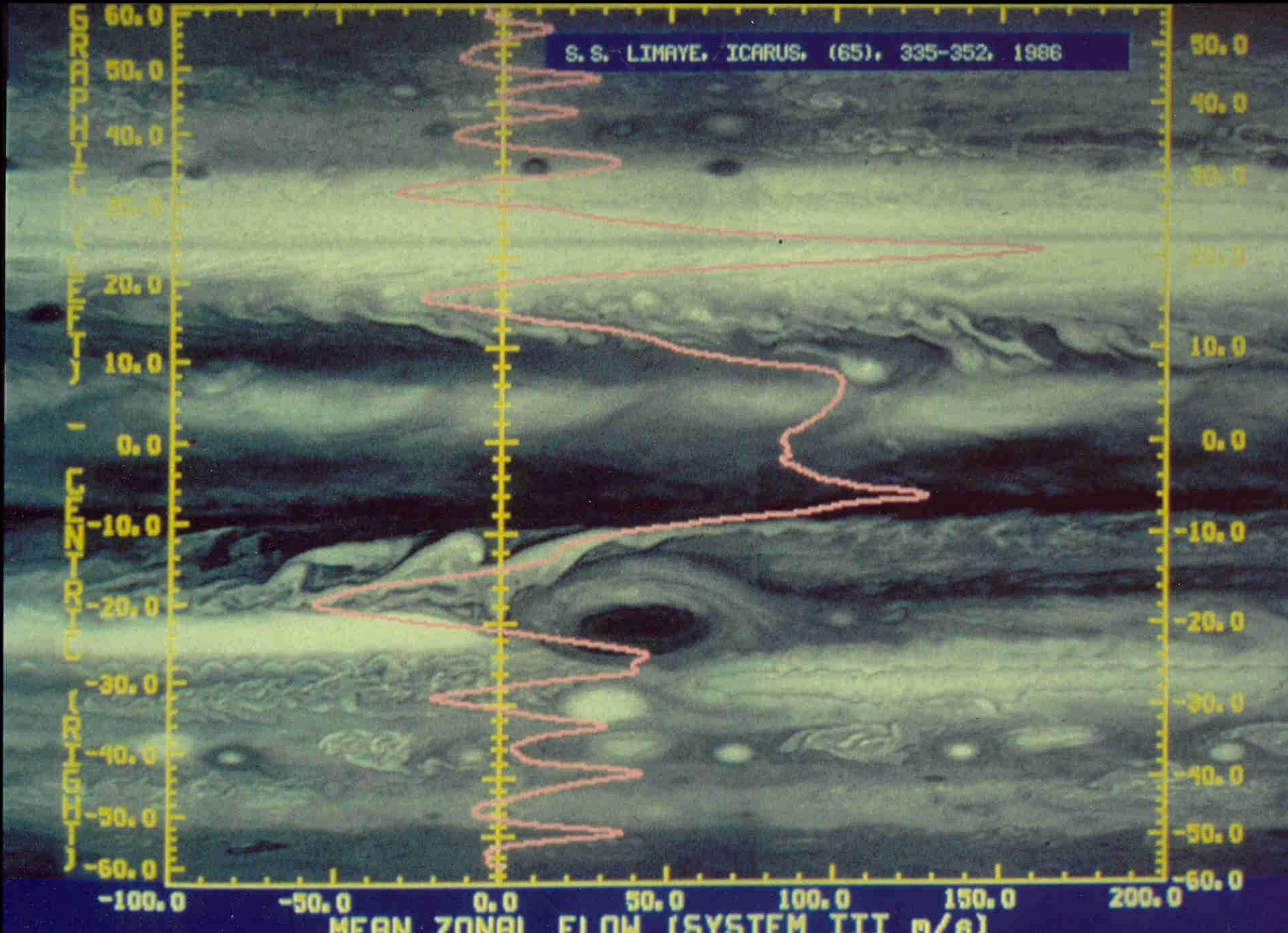
longitude

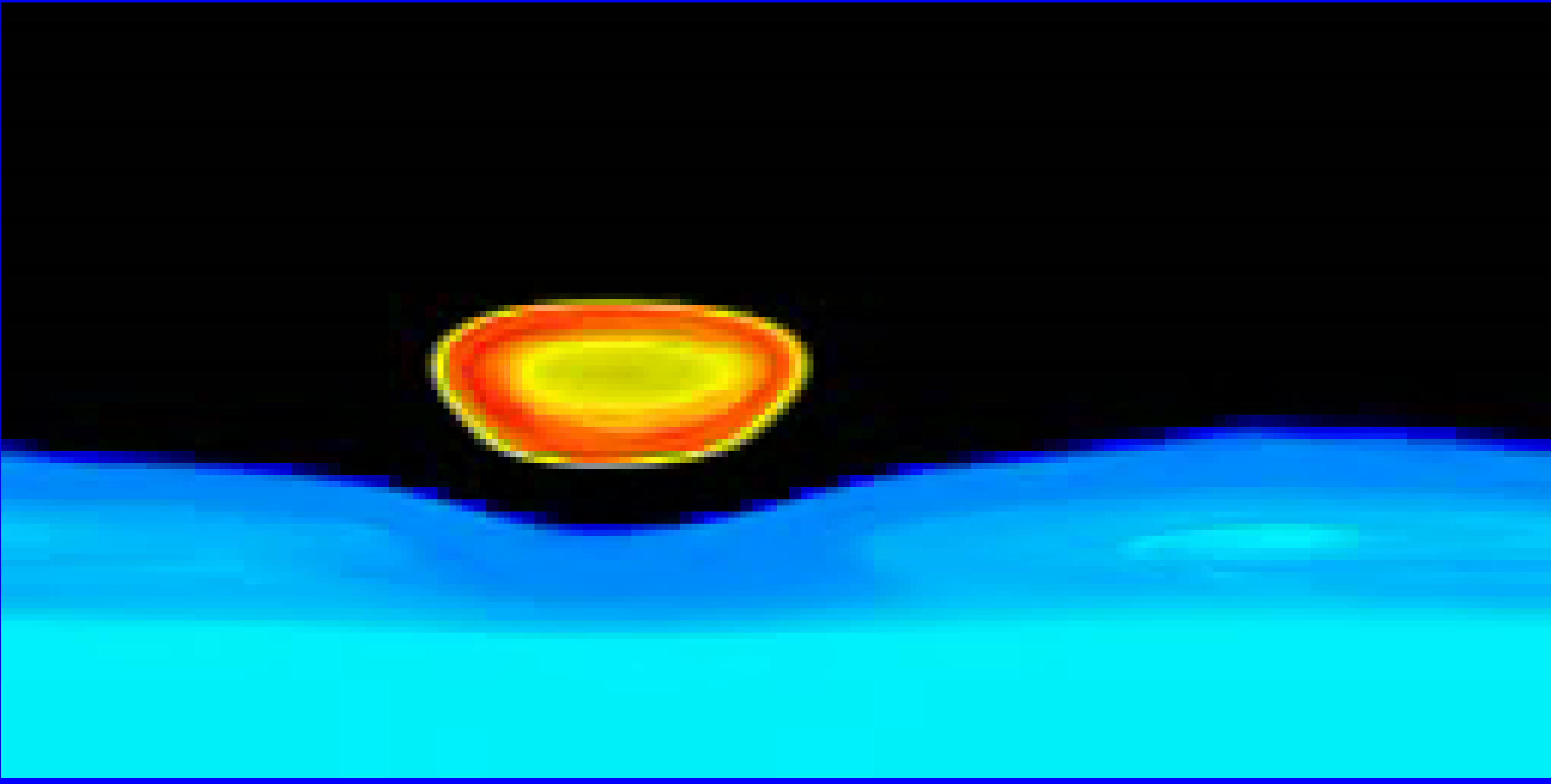


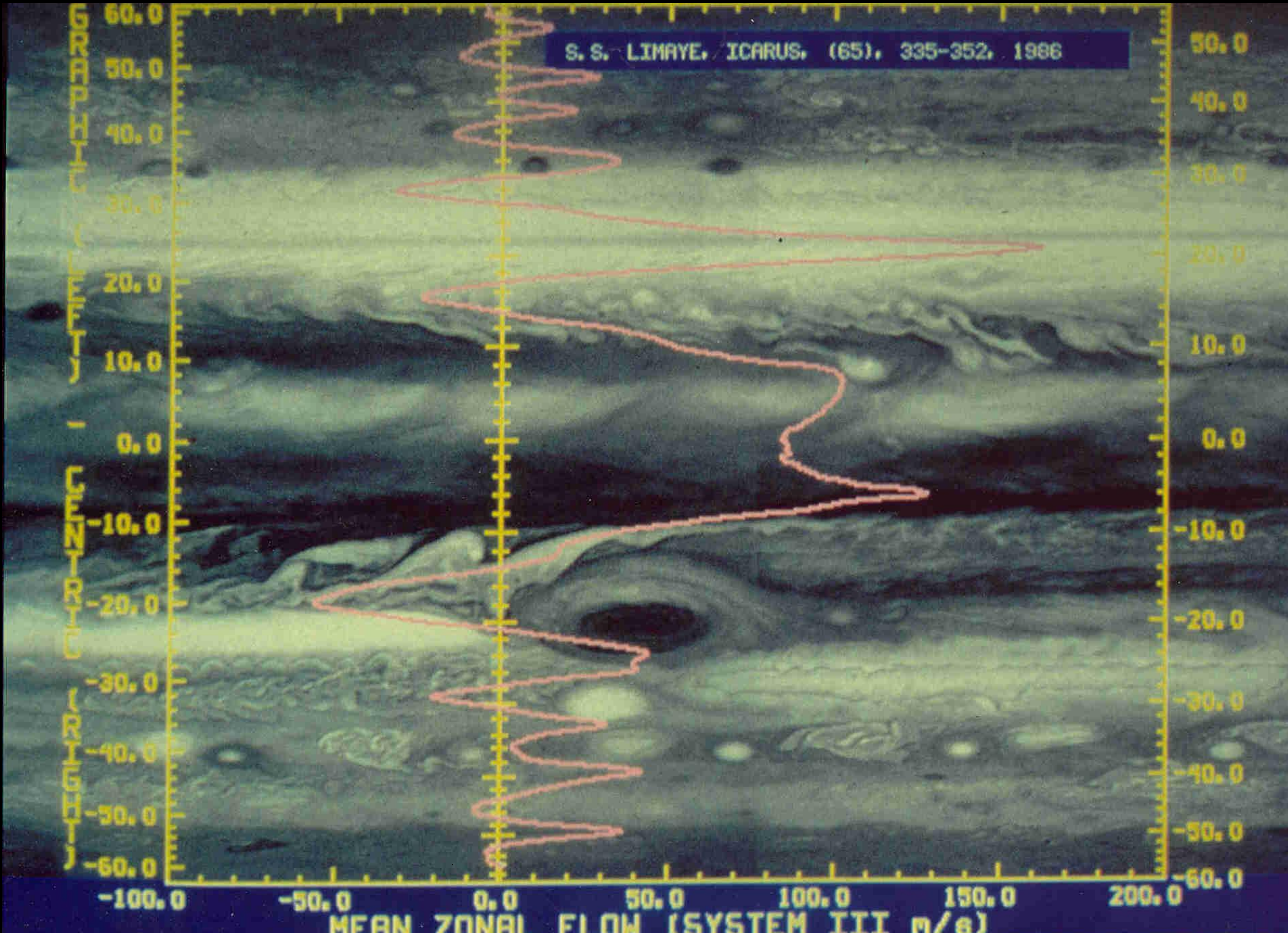
S. S. LIMAYE, ICARUS, (65), 335-352, 1986
GRAPHIC (LEFT) - CENTRIC (RIGHT)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
MEAN ZONAL FLOW (SYSTEM III m/s)

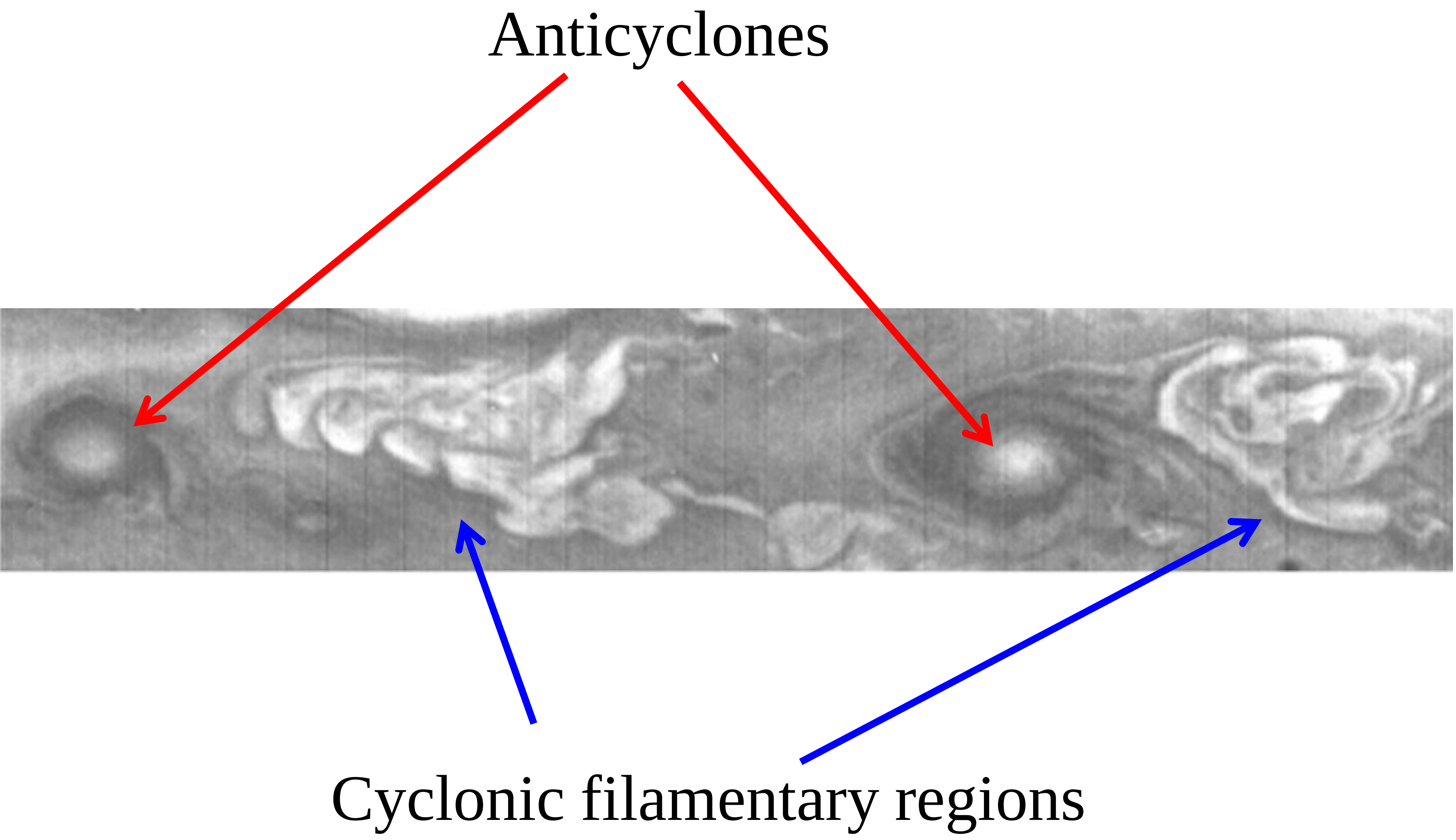
Great Red Spot is Hollow

Hollow Vortices are often unstable and turn themselves “inside out”

Hollow Vortices can be stabilized by one (and for the Red Spot, two) jumps in the zonal PV




S.S. LIMAYE, ICARUS, (65), 335-352, 1986
GRAPHIC (LEFT) - CENTRIC (RIGHT)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
MEAN ZONAL FLOW (SYSTEM III m/s)

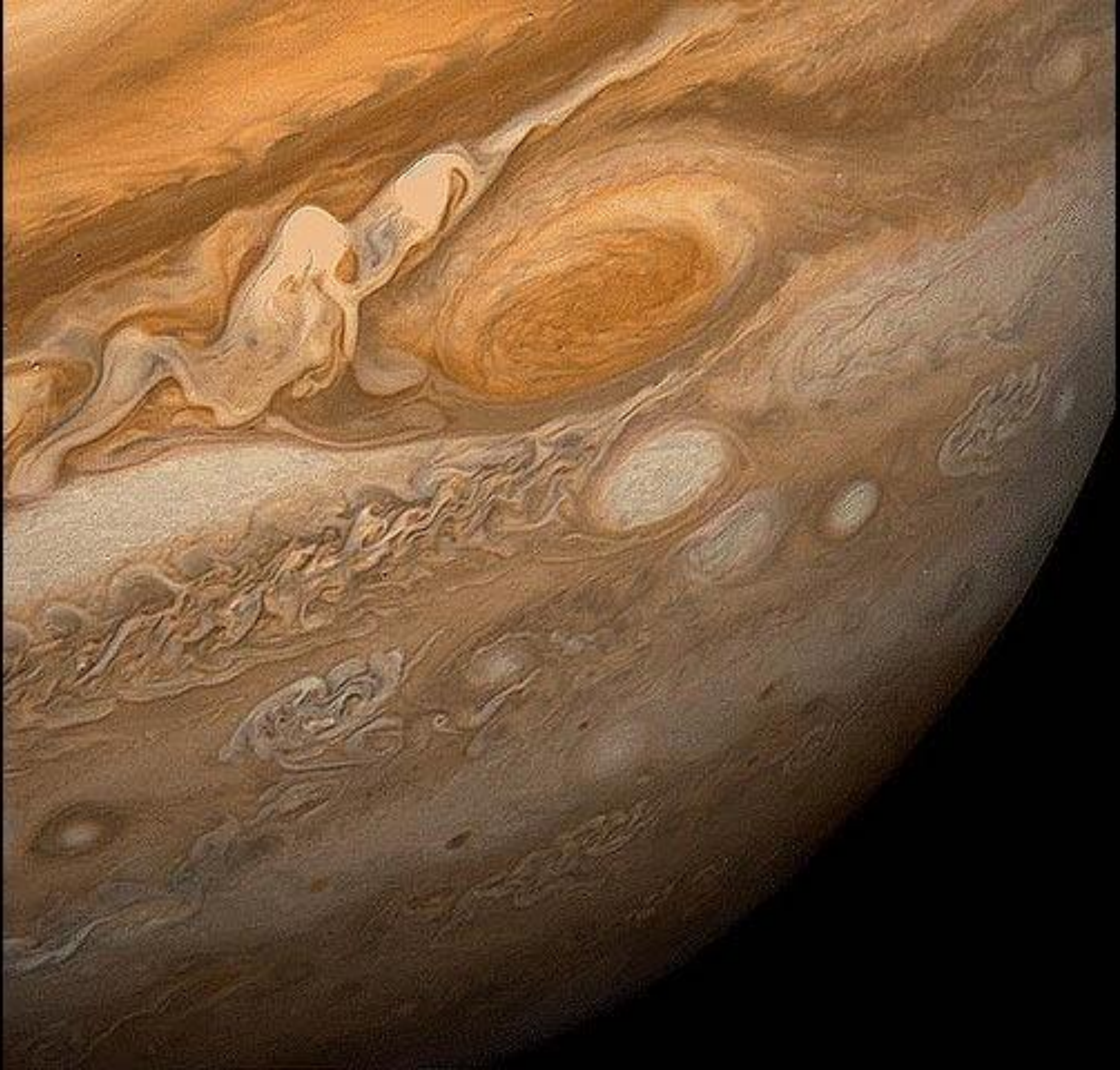

Anticyclones
Cyclonic filamentary regions

Streamlines are not particle pathlines

- Clouds are NH_3 ice crystals
- Created with cooling, destroyed with warming
- Due to 3D secondary flow:
  - Anti-cyclonic regions have upwelling
  - Cyclonic regions have down-welling
- In a sub-adiabatic atmosphere upwelling cools the flow

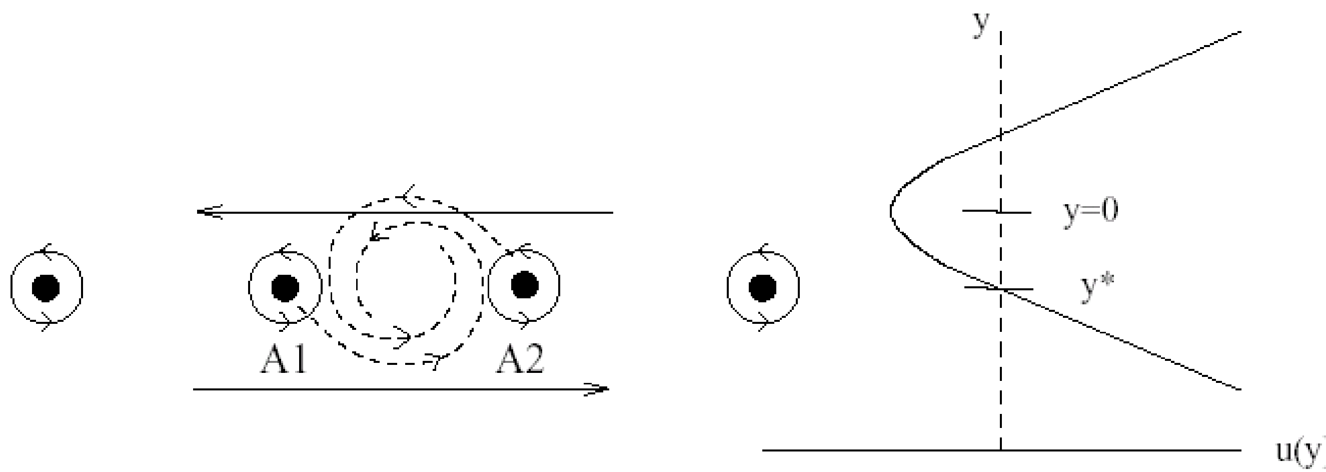
Rows of Anti-cyclones

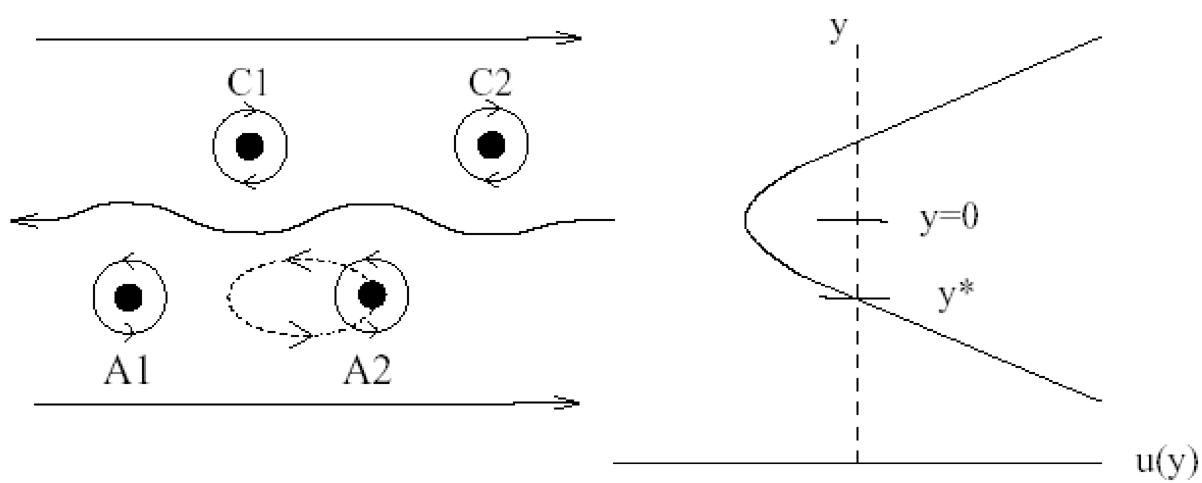
- Except for the Great Red Spot, the anti-cyclones do not occur as single vortices.
- They occur in rows (at a constant latitude).
- Each latitude corresponds to a peak of a westward jet (or just to its poleward side).

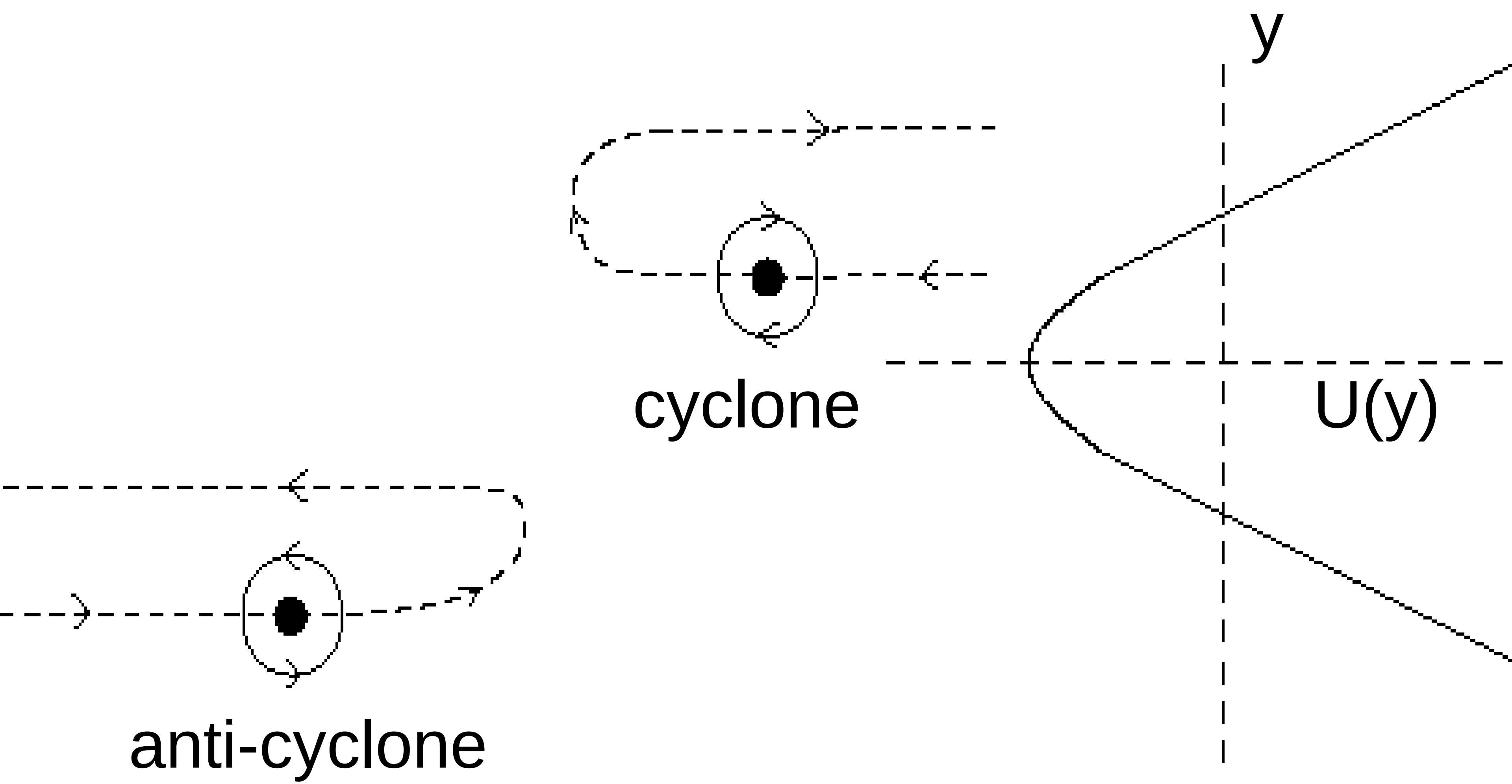


The Case for Cyclones

- Dynamically necessary to prevent anti-cyclones from merging
- Dynamically necessary to change drift directions of the anti-cyclones
- Allowed by the equations of motion (3D, 2D-shallow-water, 2D-quasi-geostrophic)

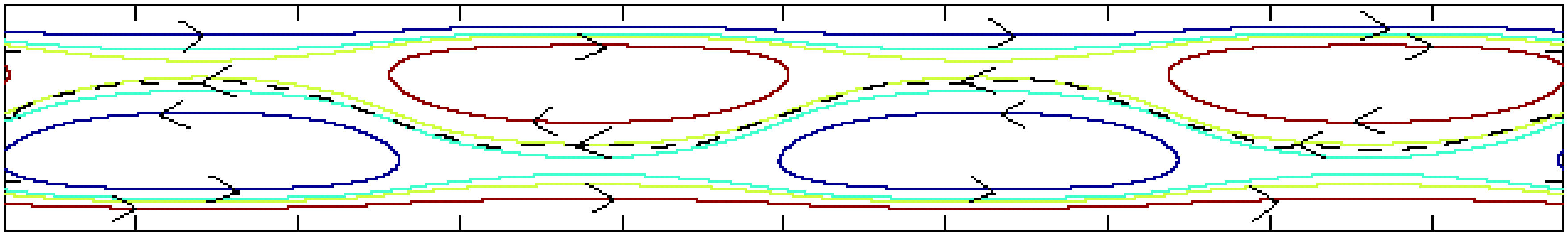

A1
A2
y
y=0
y*
u(y)


C1
C2
A1
A2
y
y=0
y*
u(y)

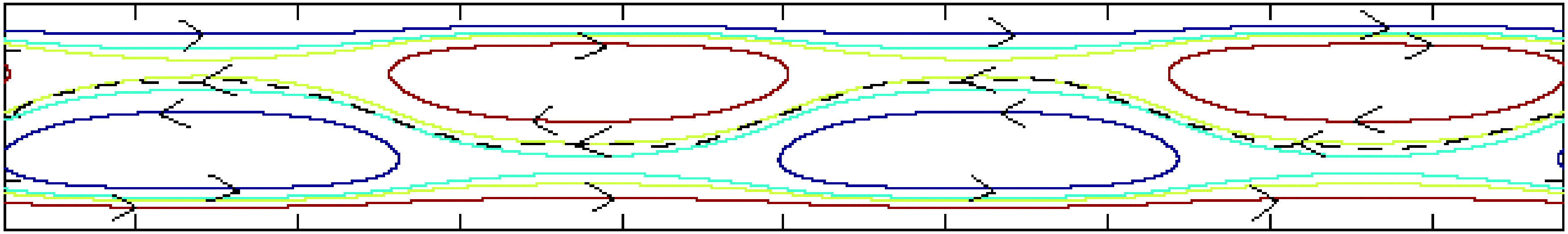


y
cyclone
U(y)
anti-cyclone

In quasi-geostrophic simulations cyclones and anti-cyclones are treated the same



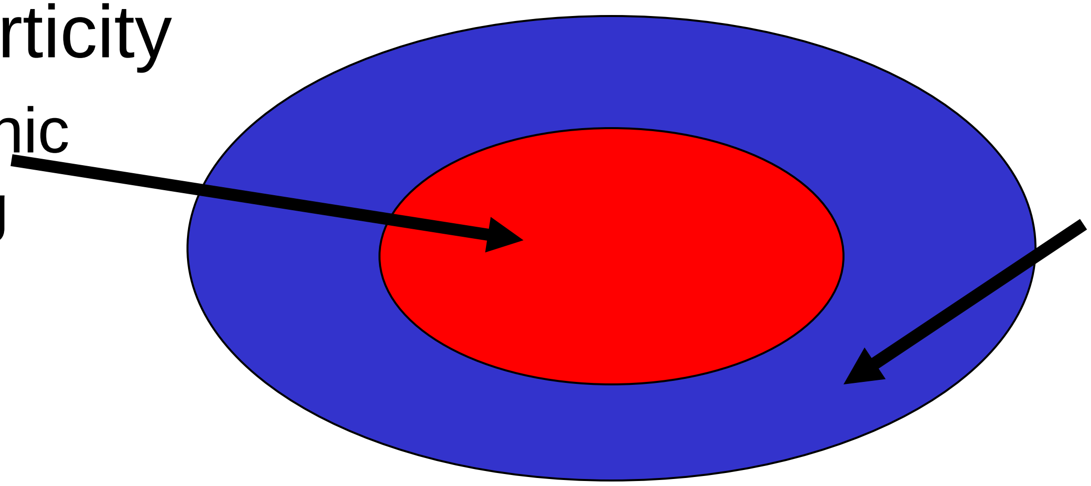
Only One Great Red Spot



"Anti-cyclone" refers to the potential vorticity

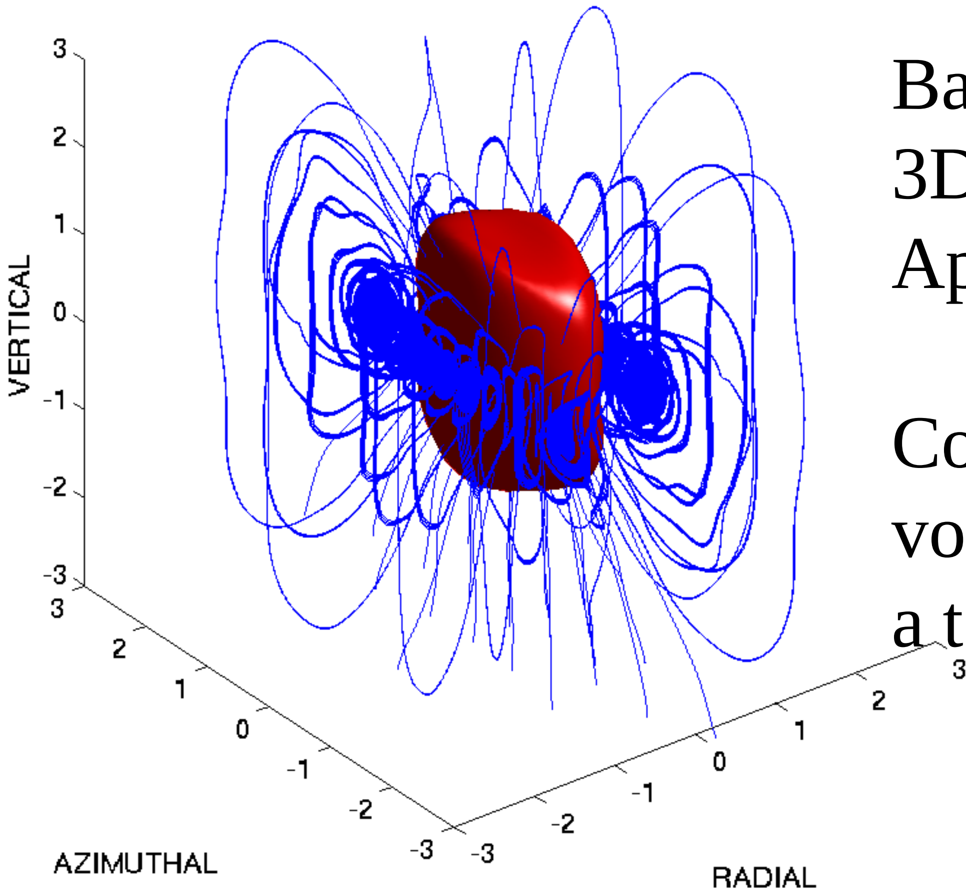
Vortex is a compact of potential vorticity; total circulation of vorticity is zero (shielded).

An anti-cyclone (like the Red Spot) is surrounded by a cyclonic ring of vorticity



Persistent 3D Vortices

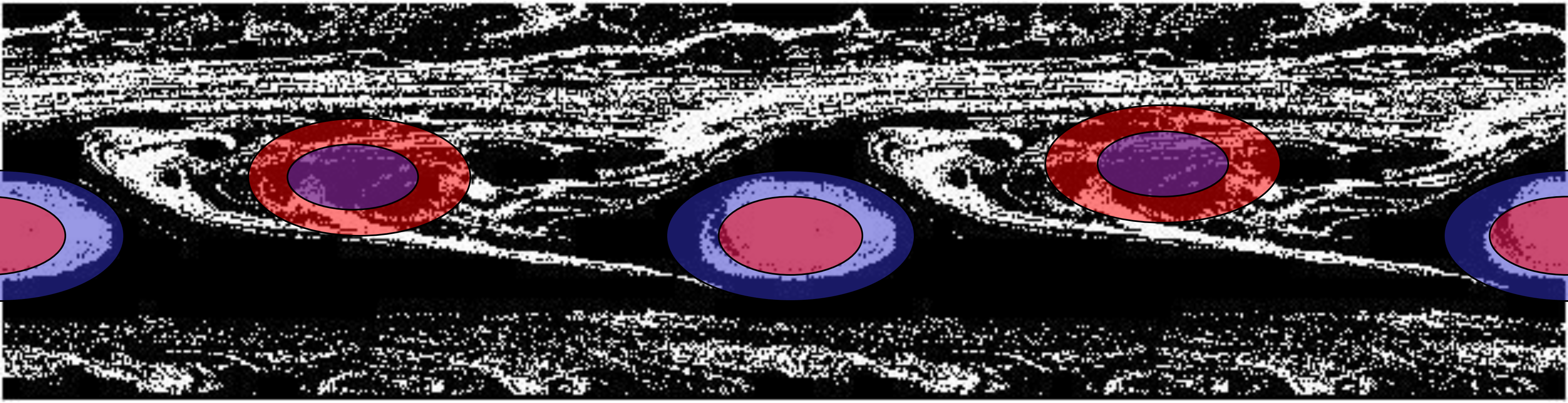
Physics is 3D vortices, rather than 2D Taylor columns

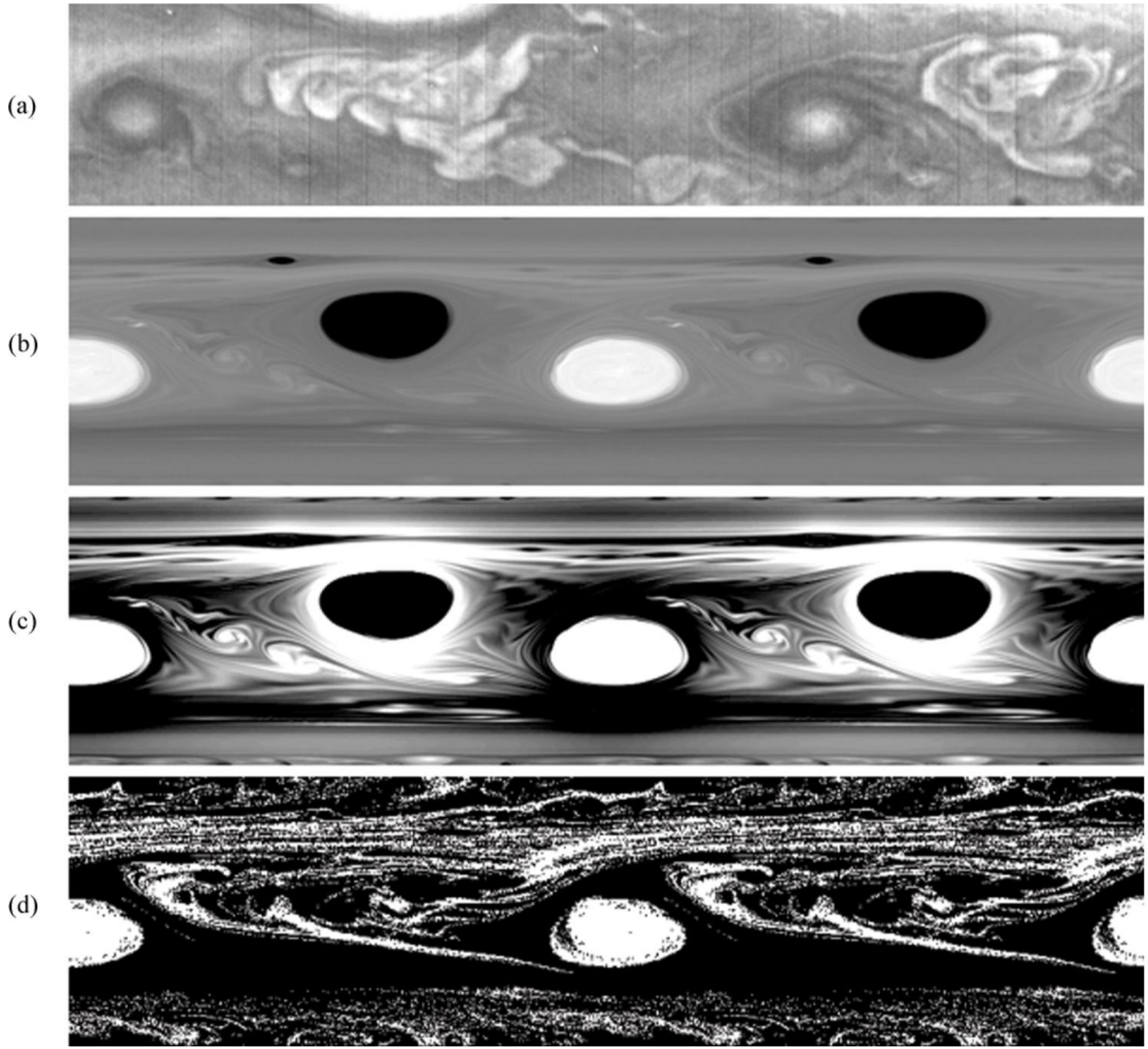


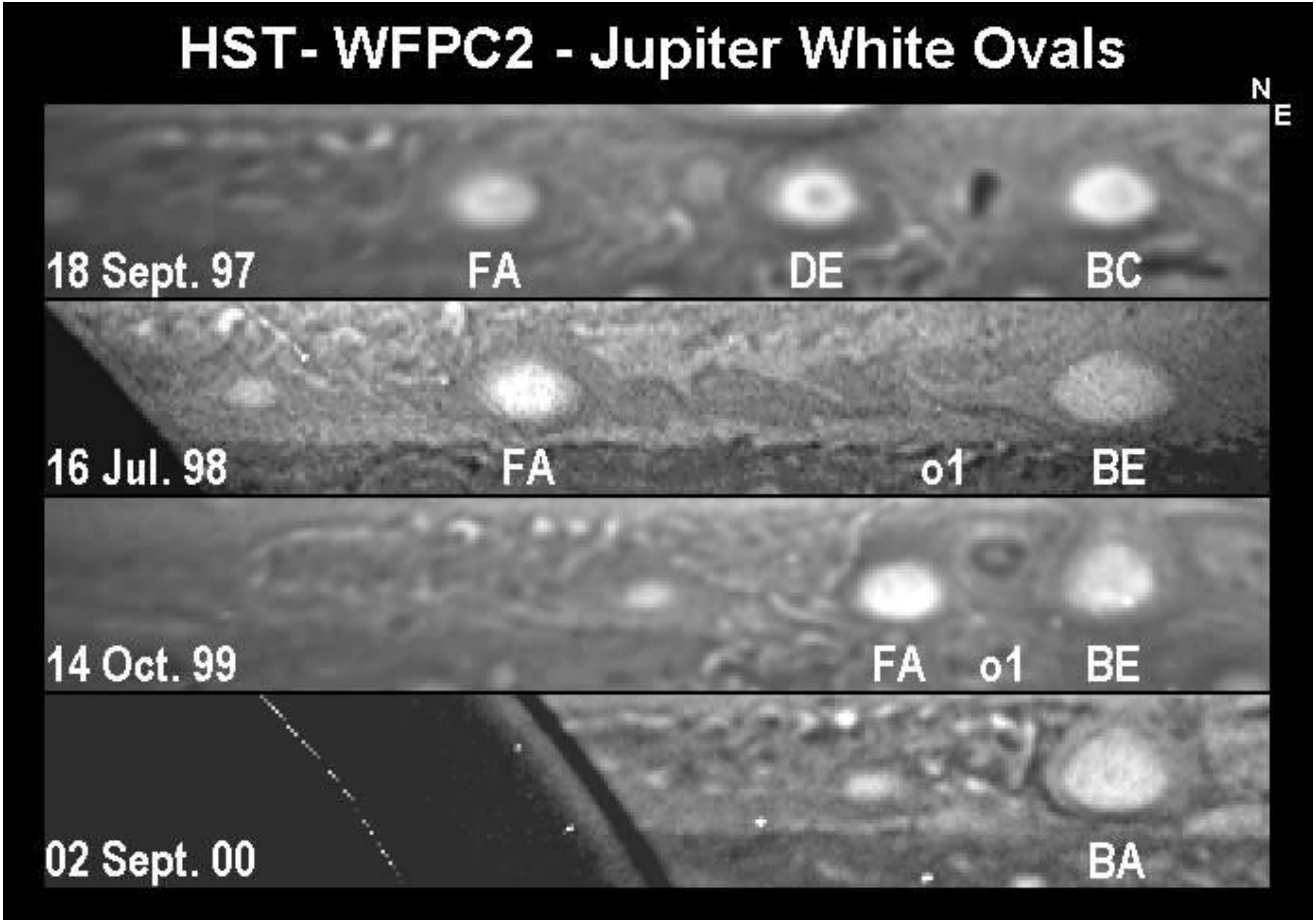
Barranco & Marcus
3D, rotating, stratified
Ap.J. 2005, JCP 2006

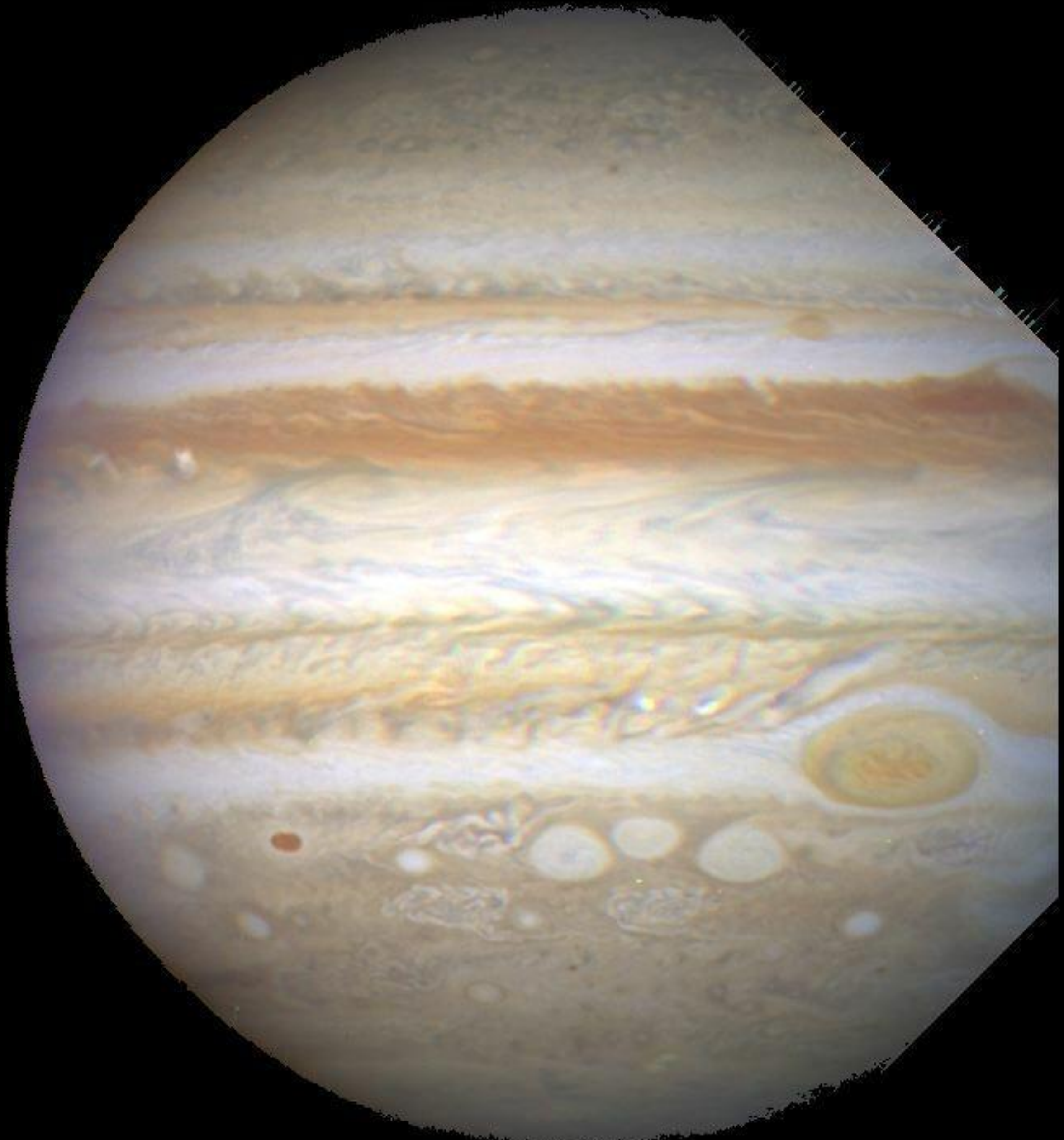
Compact vortex, with vortex lines forming a torus

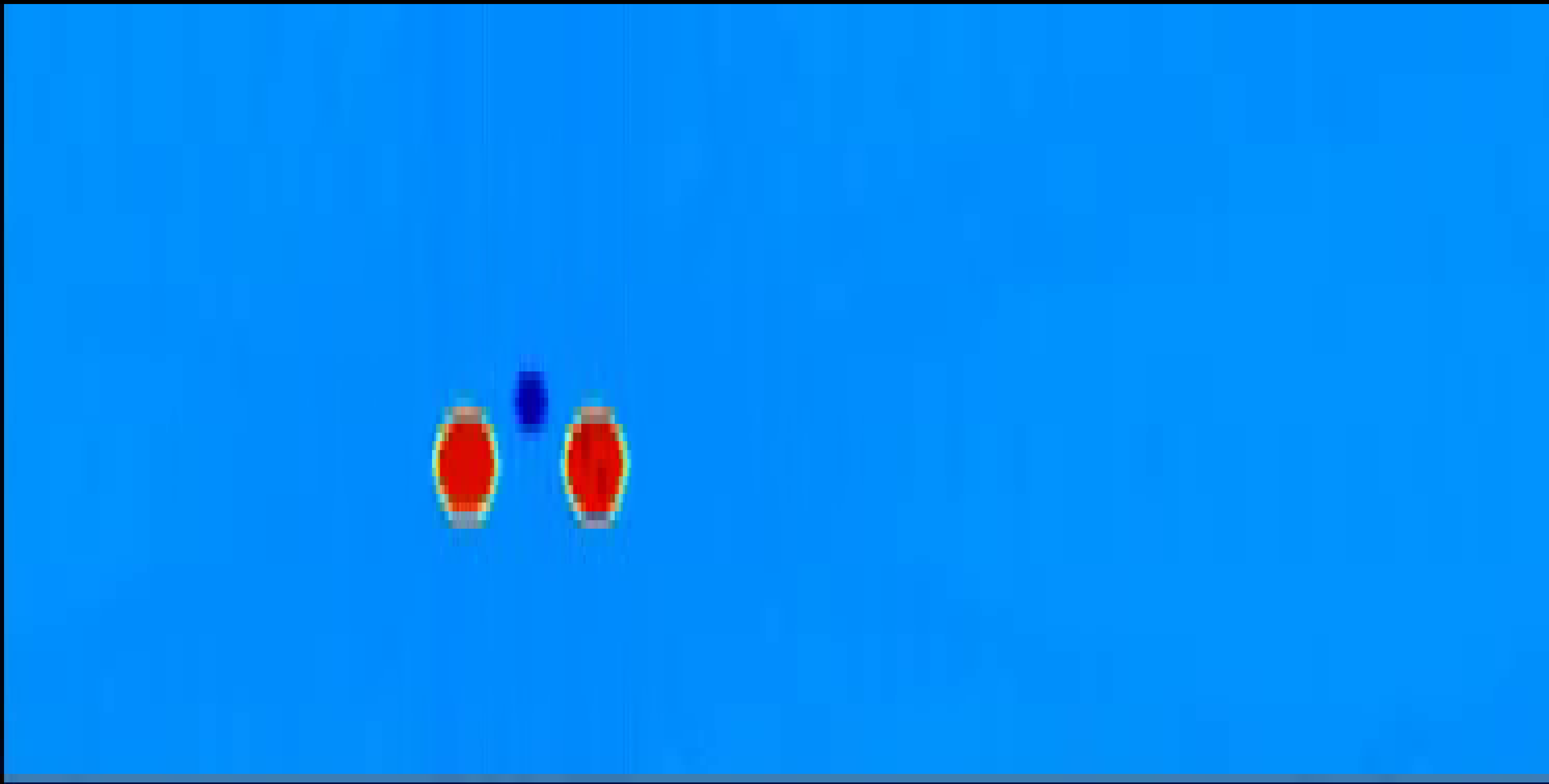
No dissipation



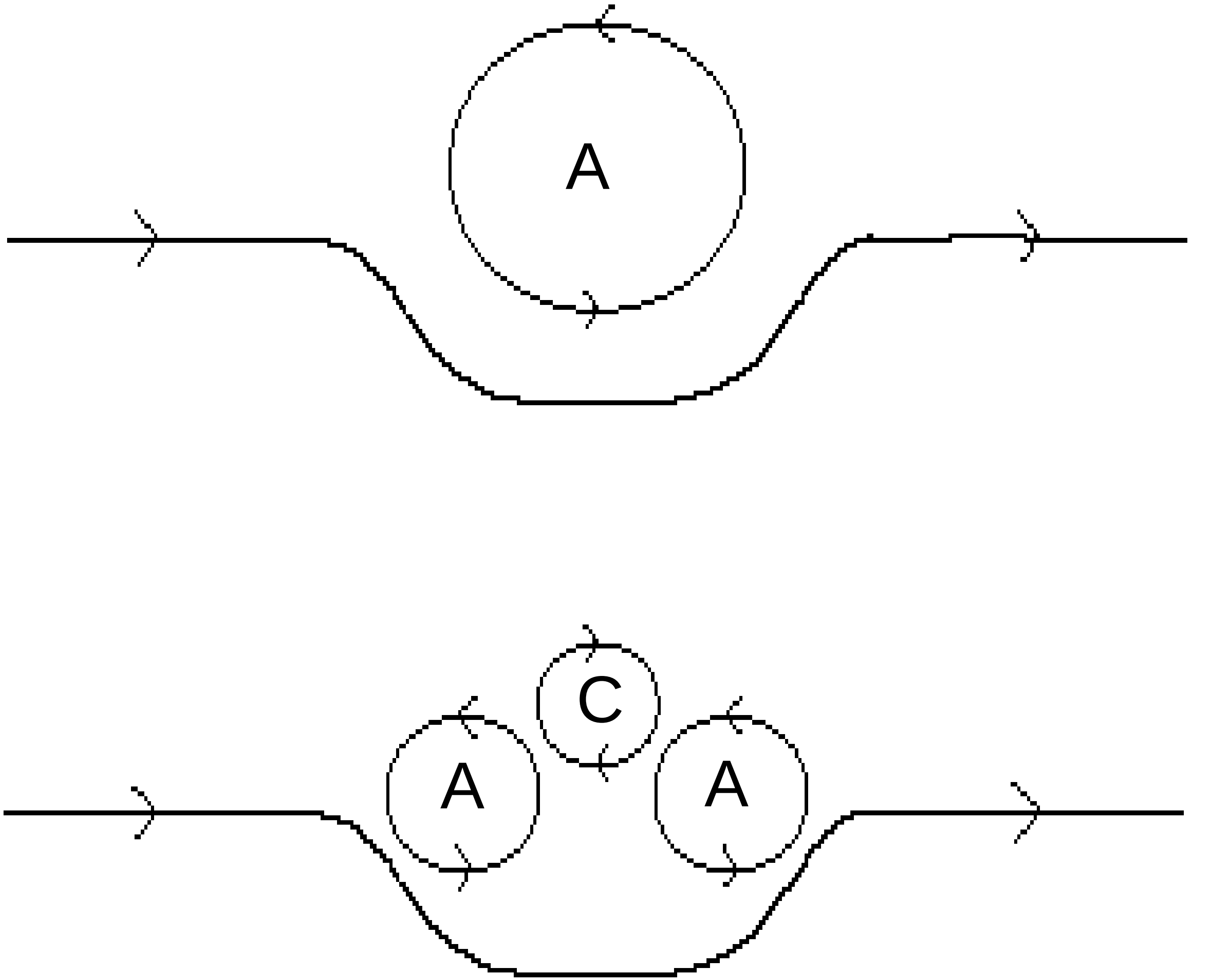

(a)
(b)
(c)
(d)


HST- WFPC2 - Jupiter White Ovals
N
E
18 Sept. 97
FA
DE
BC
16 Jul. 98
FA
o1
BE
14 Oct. 99
FA
o1
BE
02 Sept. 00
BA

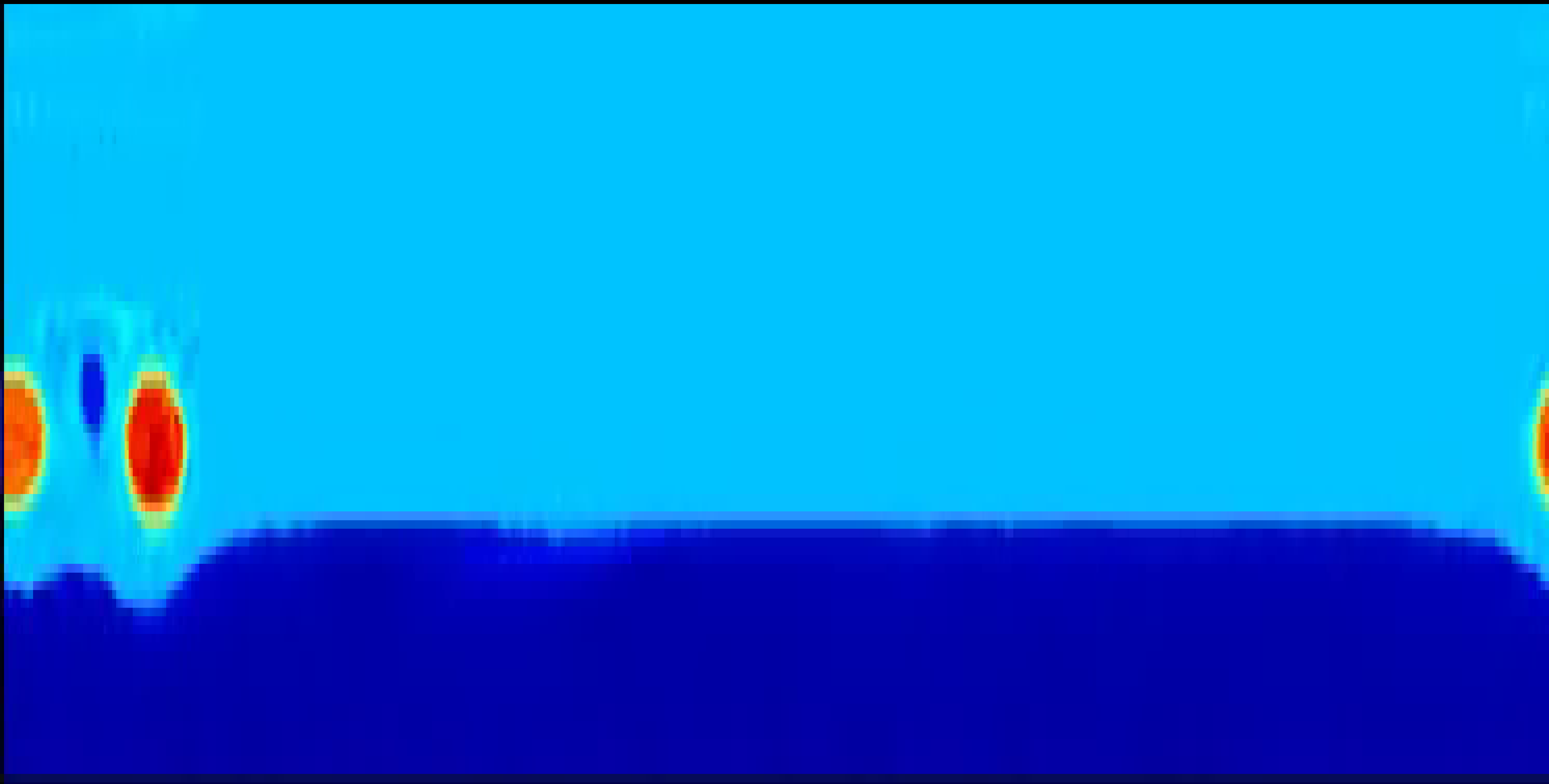


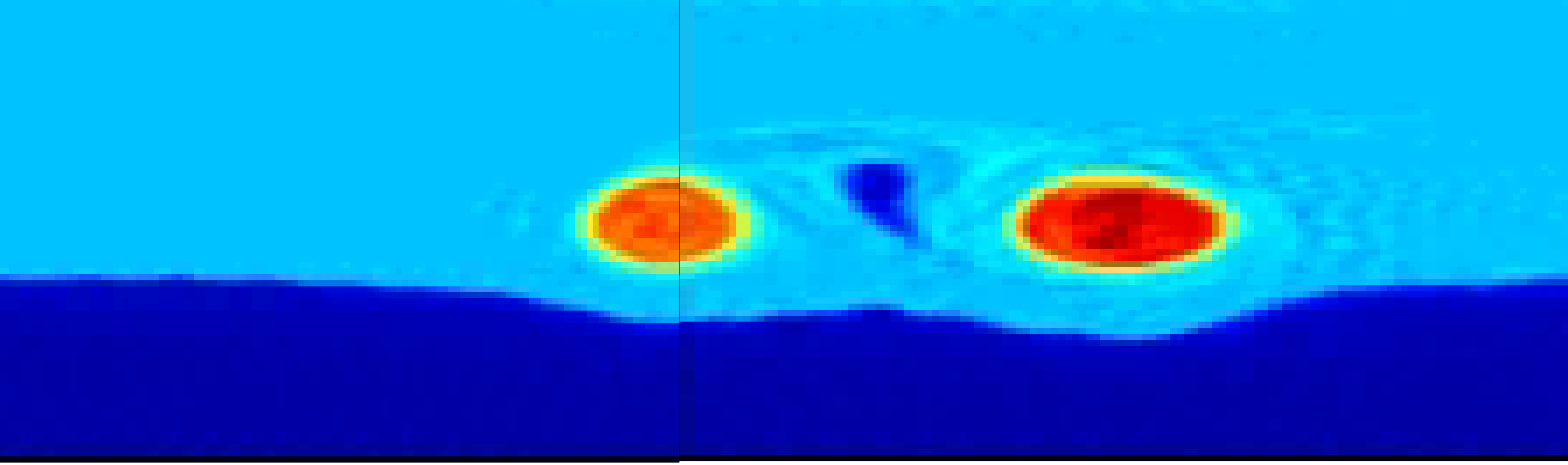


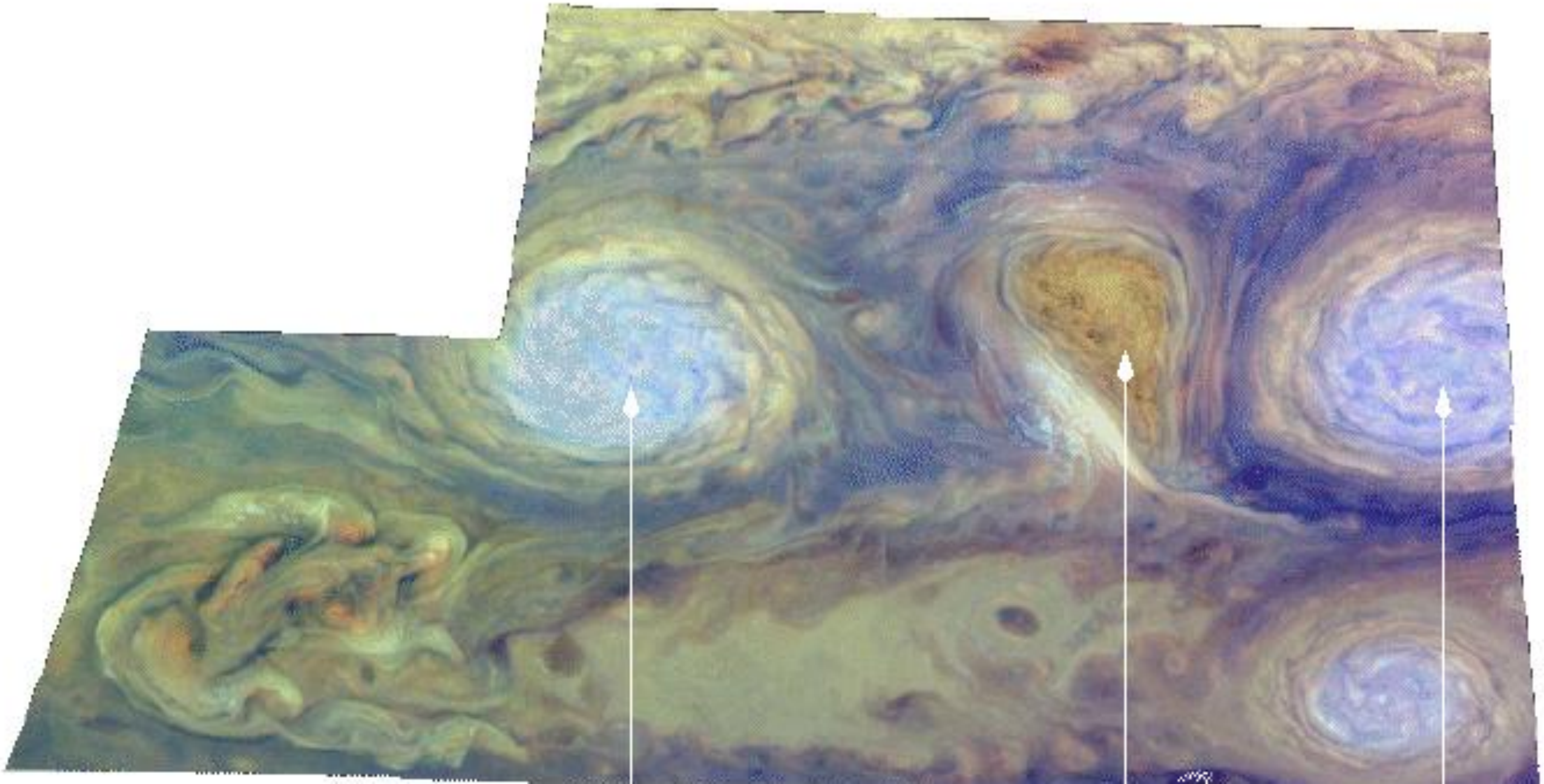

Jet Stream
Monday
Oct 08, 2007
C
L
01 Oct 2007 17:03 GMT / 01 Oct 2007 01:03 PM EDT



Cyclone below critical value

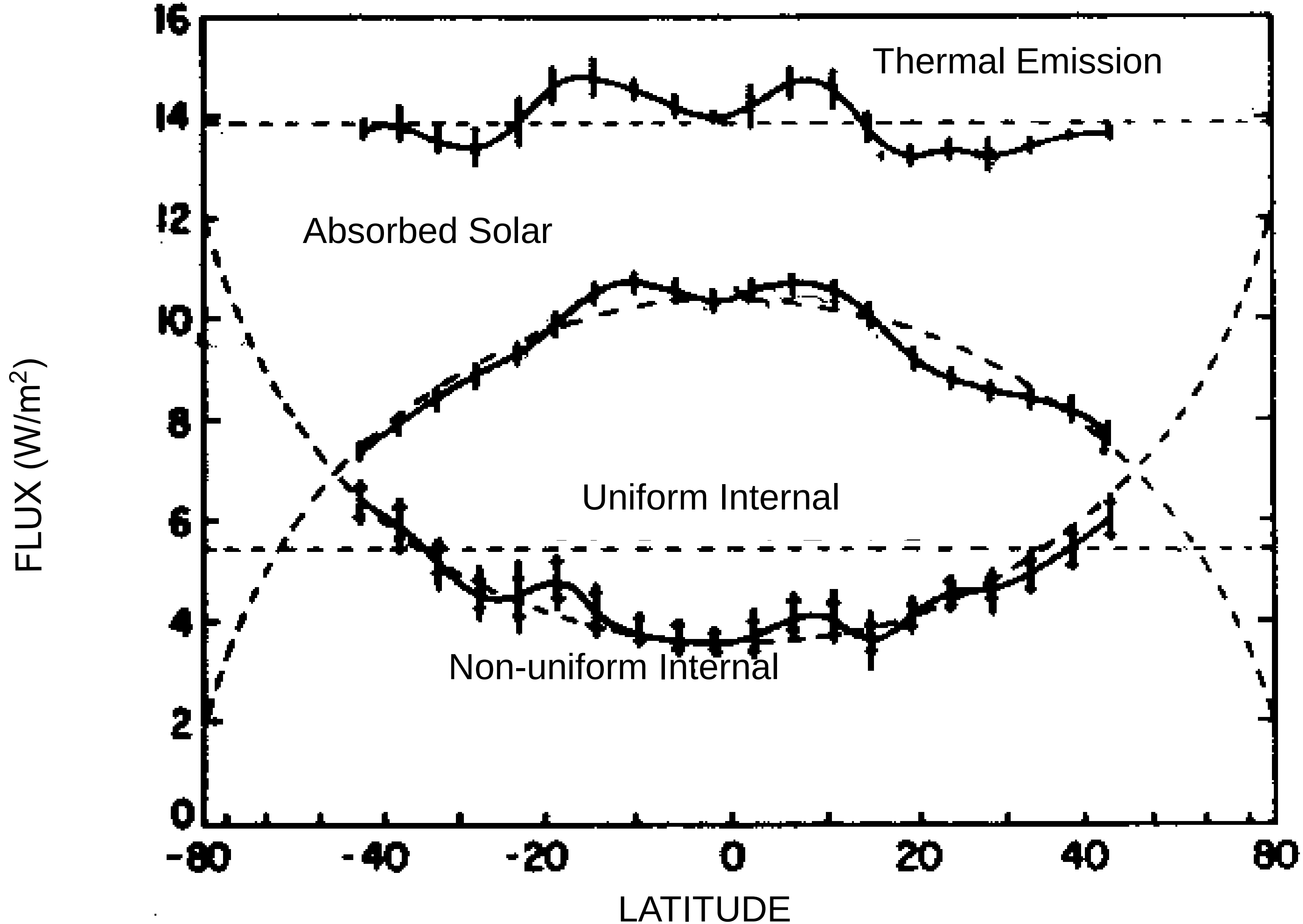






Need for Heat Transport

- Voyager (1979) used several instruments to look at multiple wavelengths to measure temperature at the cloud tops.
- Surprise! The temp. was isothermal in longitude ± 4K. least half of the heat deposited from the Sun is captured and absorbed in the cloud layer



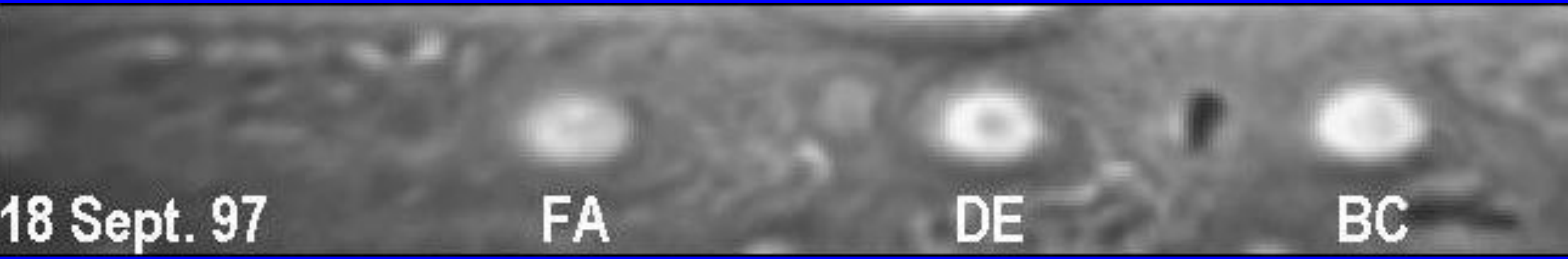
Thermal Emission
Absorbed Solar
Uniform Internal
Non-uniform Internal
FLUX (W/m^2)
LATITUDE
16
14
12
10
8
6
4
2
0
-80
-40
-20
0
20
40
80

Need for Heat Transport

- Modeling the top of the convective zone with a perfect conductor – still leaves a pole-equator heat differential of 30K

- Including the mixing of heat with the meriodional velocity of the vortex street did not significantly decrease the pole-equator heat differential

Chaotic Mixing of Heat



If chaotic rows of vortices are necessary for heat transfer, then the mergers of the 3 White Ovals in 2000 would have lead to a barrier to heat transport at 34^0S

PSM Nature 2004

No Thermometers on Jupiter

- No space or ground-based telescope since Voyager can measure cloud top temperature
- Limited observations coupled with models would work if there were no clouds.
- Need to infer temperature changes
- But first, let’s revisit the measurements of velocities

What Determines the Aspect Ratio (height/radius) of a Vortex?

Competition between stratification (pancakes) and rotation (Taylor columns)

Stratification

- Brunt-Väisälä frequency :

$$N = \sqrt{-\frac{g}{\rho}\frac{\partial \rho}{\partial z}} \quad \text{(rad/s)}$$

LIMITS THE MOTION ALONG THE DENSITY GRADIENT

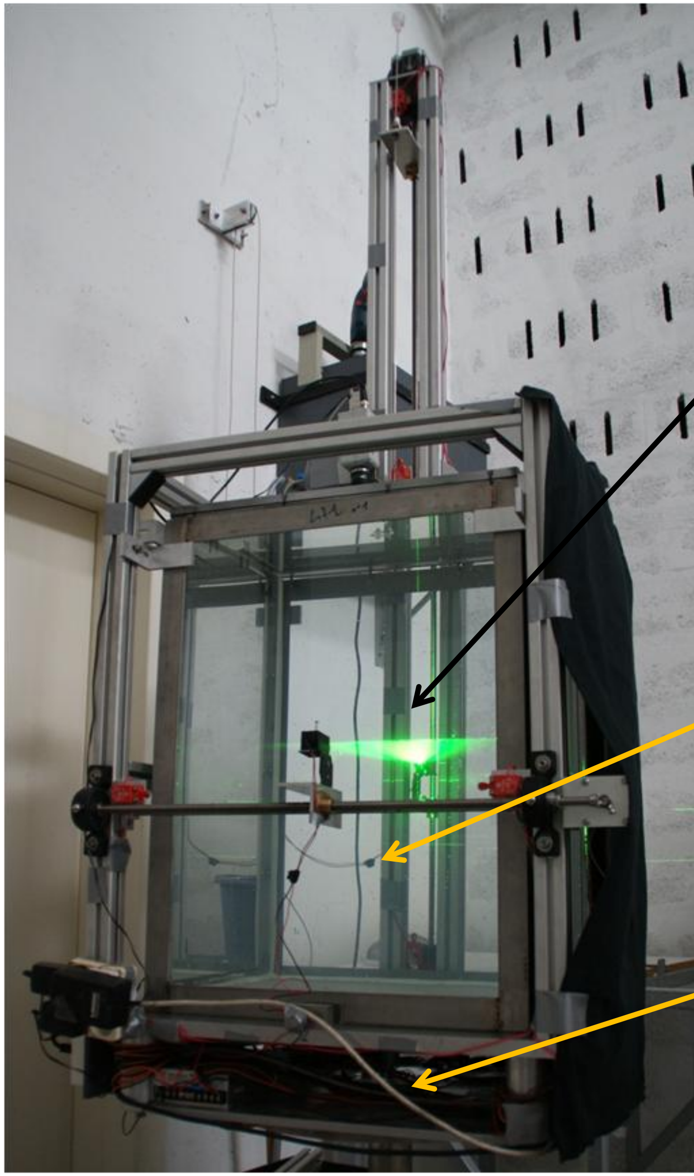
Rotation

- Coriolis parameter :

$$f = 2\Omega \sin\phi \quad \text{(rad/s)}$$

HOMOGENIZES THE FLOW ALONG THE AXIS OF ROTATION

Oriane Aubert, Michael le Bars, Patrice Le Gal and PSM



Vertical and horizontal laser sheets and cameras

Linear stratification with salty water

N_{out} from 1.2 to 1.8 rad/s

Rotating table

f from 1.8 to 7 rad/s

Numbers

- **Rossby** $Ro = U/fL$

  0.5 to 0.02

- **Froude** $Fr = U/LN_{out}$

  2 to 0.2

- **Ekman** $Ek = /fH^2$

  10^{-3} to 10^{-5}

- **Schmidt** $Sc = /k$

  700

Creating Vortices

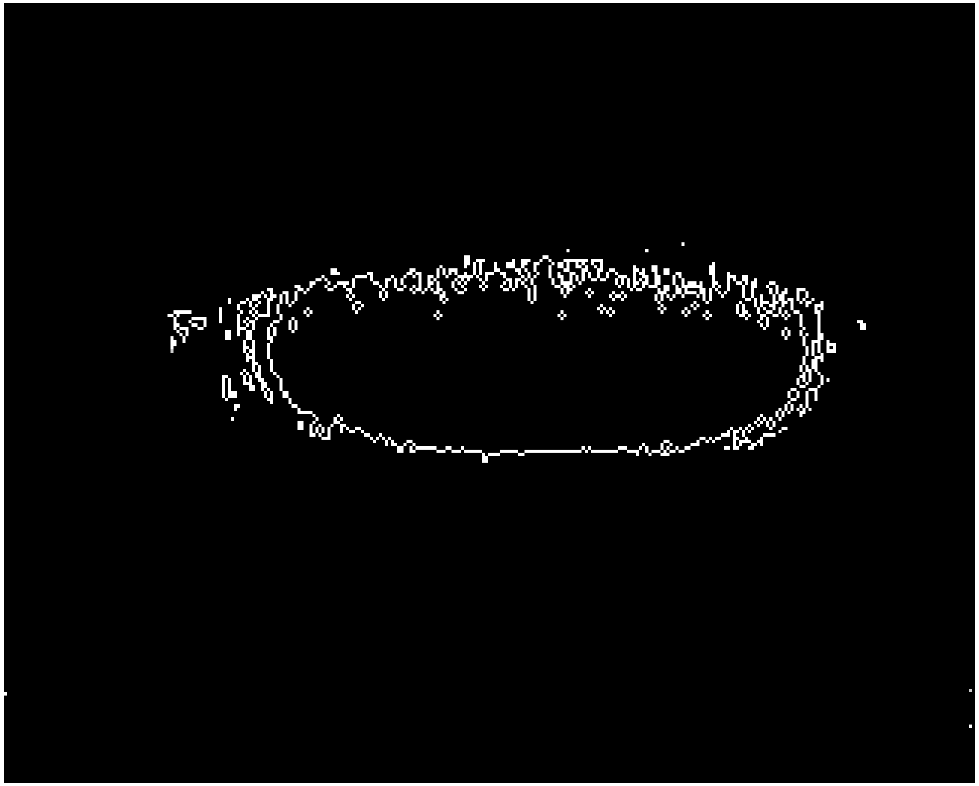
Create stratified fluid with classical double bucket method, so N_{out} is uniform

Rotate table up to desired speed (wait)

Inject small volume of fluid of uniform density ρ_0 into fluid at height z_0, where $\rho(z_0) = \rho_0$

Wait while vortex undergoes hydrostatic adjustment (fast, vertical) and geostrophic adjustment (slow, horizontal)

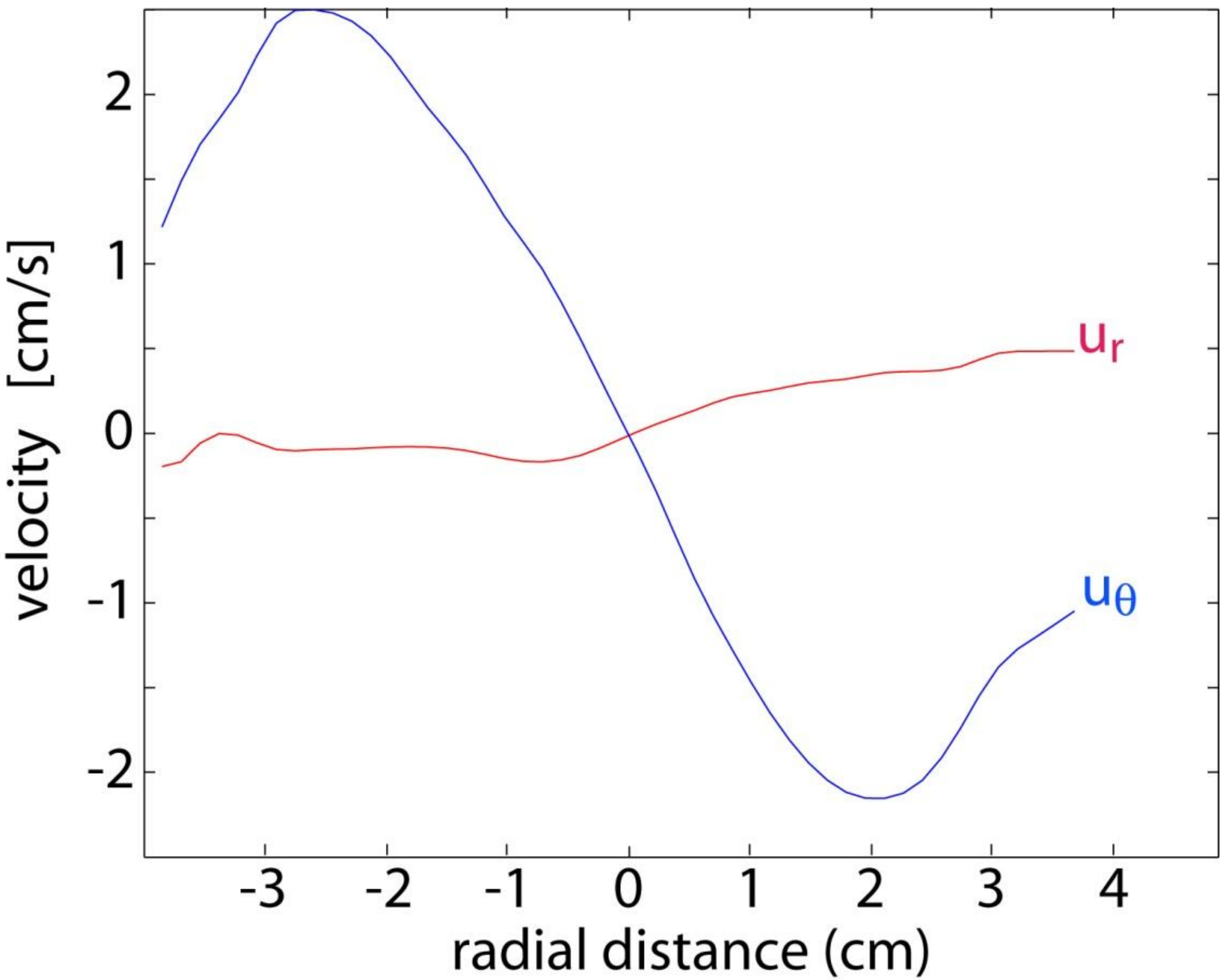
Side View

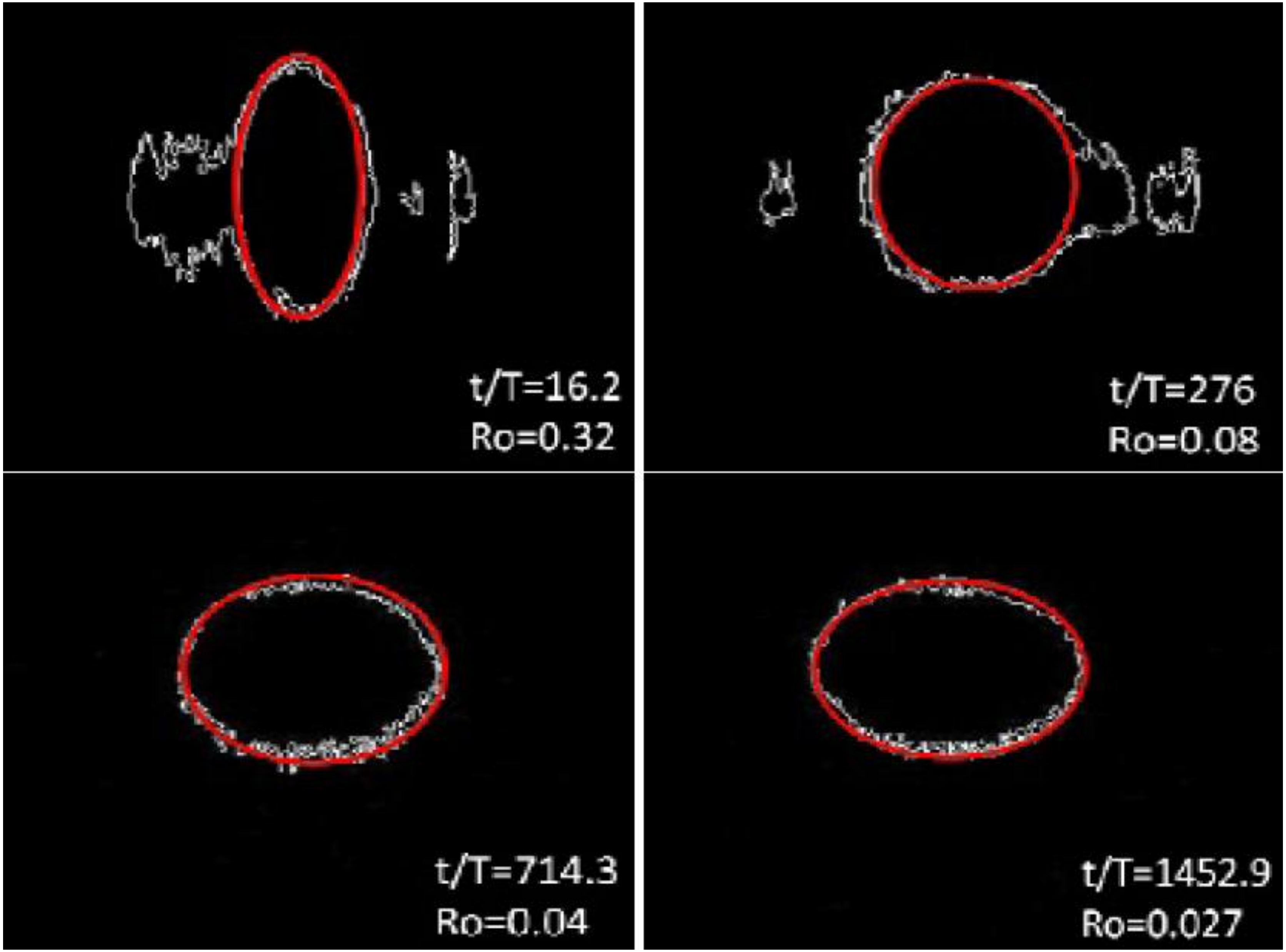


Fluorescein dye

Image processed contour

PIV Measured Velocities




t/T=16.2
Ro=0.32
t/T=276
Ro=0.08
t/T=714.3
Ro=0.04
t/T=1452.9
Ro=0.027

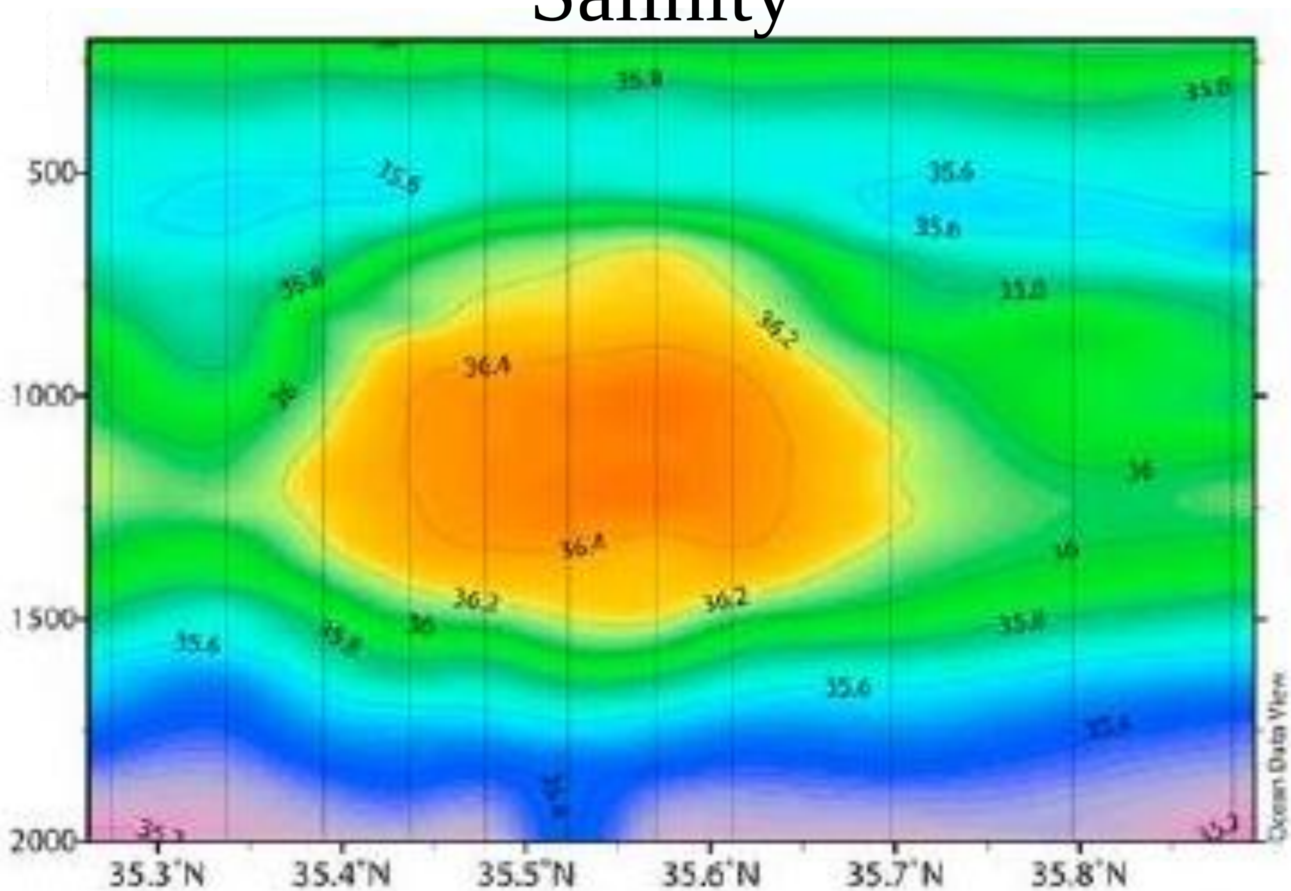
Meddies

Lifetimes up to 4 years, anticyclones, D ~ 1 km; L ~ 100 km

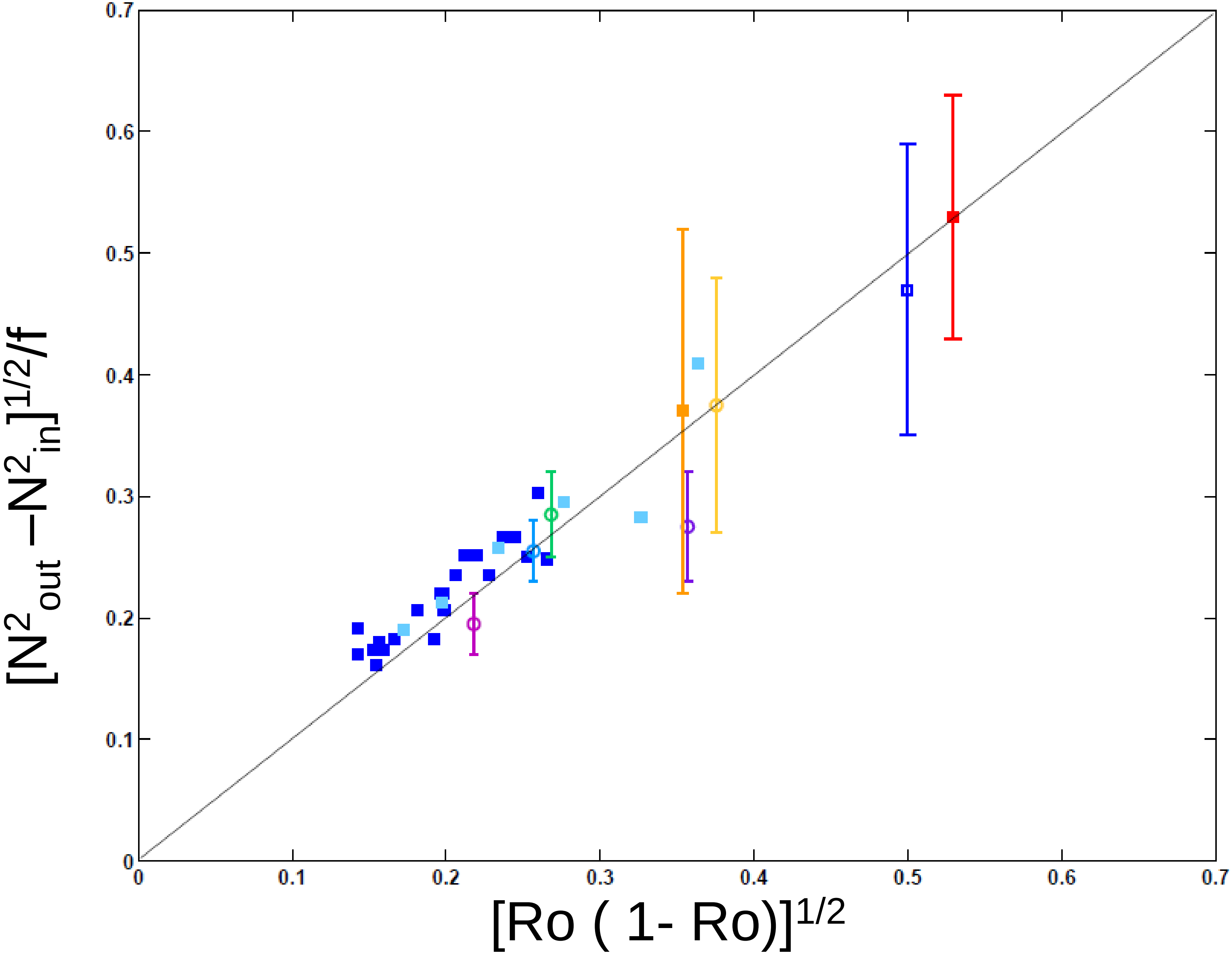
Ro, N_{out} and $N_{in} \neq 0$ have been measured

Salinity

Depth



Carton *et al.*, 2010

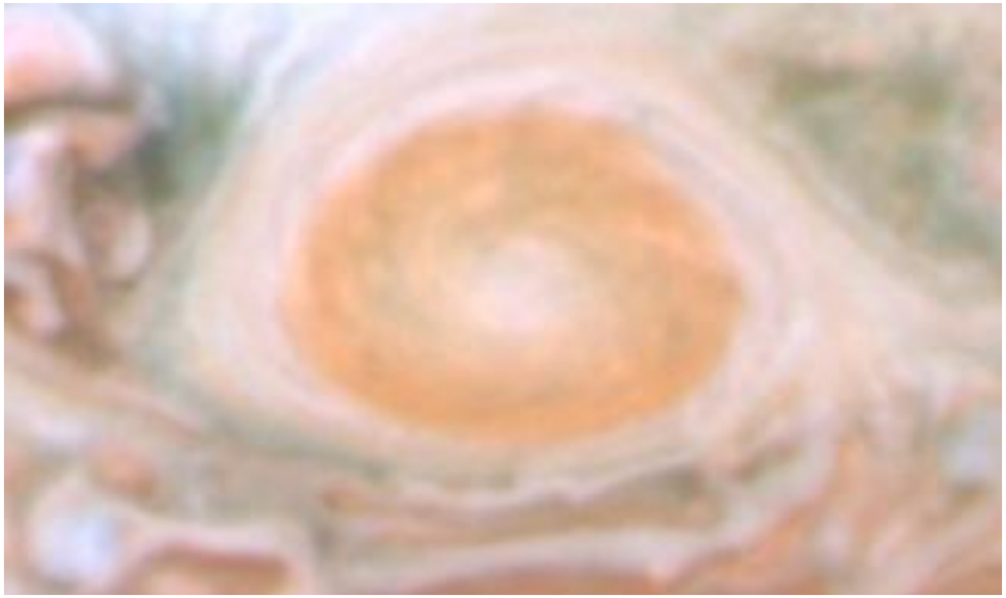


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$[N^2_{out} - N^2_{in}]^{1/2}/f$
$[Ro\ (1 - Ro)]^{1/2}$

Cause of the RED color?

Upwelling of red chromophores?

- Why 6-year wait after the Oval formed?
- Why did the color first appear in a ring?
- Why has the red color stayed in the ring for 4.5 years when the particulate mixing time is a month?



Cloud Layer is Like a Cloud Chamber

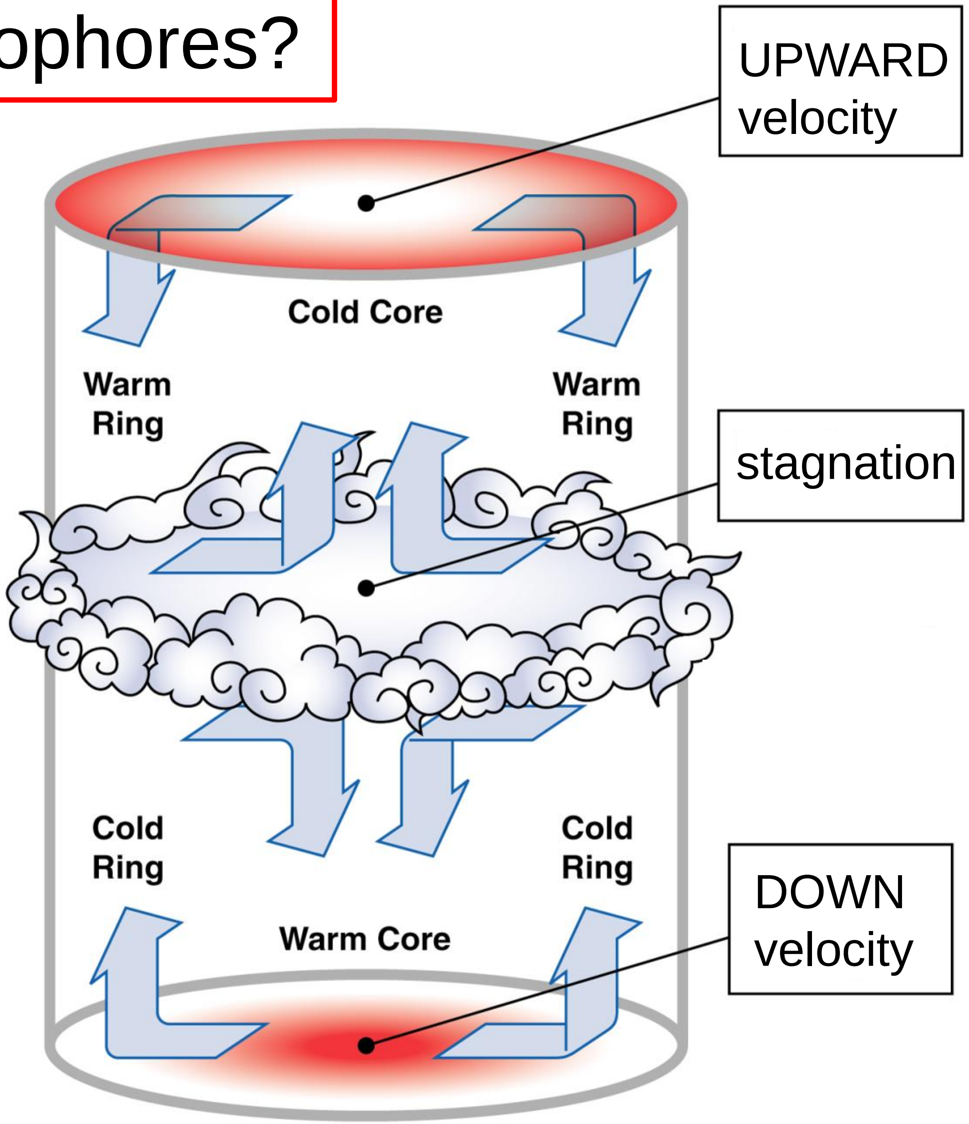
Bob West

- Solid chromophore particulates ices with ammonia ice mantles
- Temperature/pressure at their critical values for sublimation/mantling
- Red chromophores present everywhere but hidden
- Previous subtle hue changes due to small temperature changes

Cause of the RED color?

Upwelling of red chromophores?

- Why did the first appear in a ring?
- What keeps red in the ring?
- Requires 100m/s vertical velocity to dredge a pressure scale height
- Why 6-year wait?



Cause of the RED color?

Red/white color of chromophore is function of temperature

- Particulates freely mix throughout the Oval and in and out of the red annulus
- Location of ring of downward velocity is fixed
- Thus, location of warm RED ring is fixed