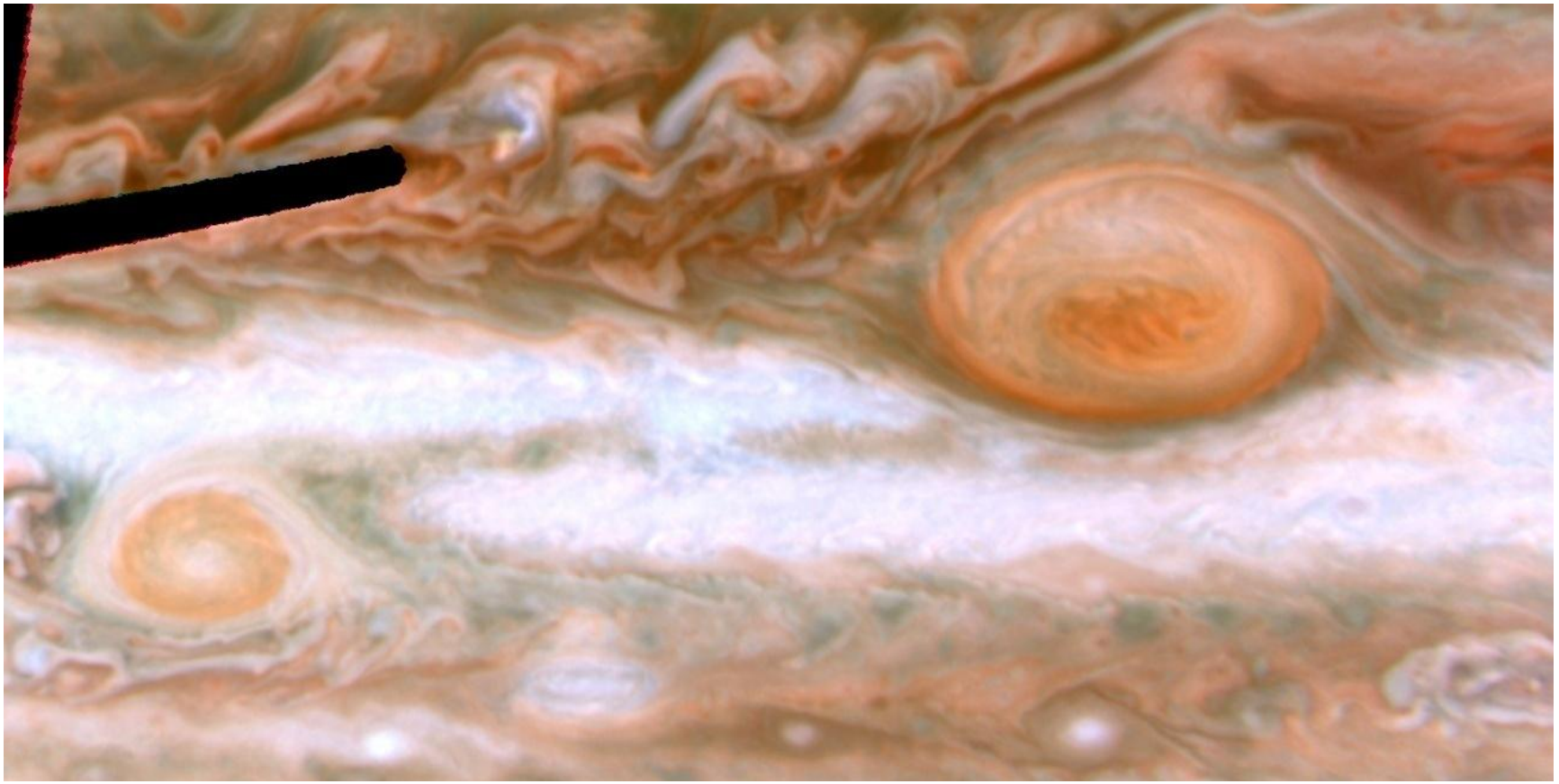
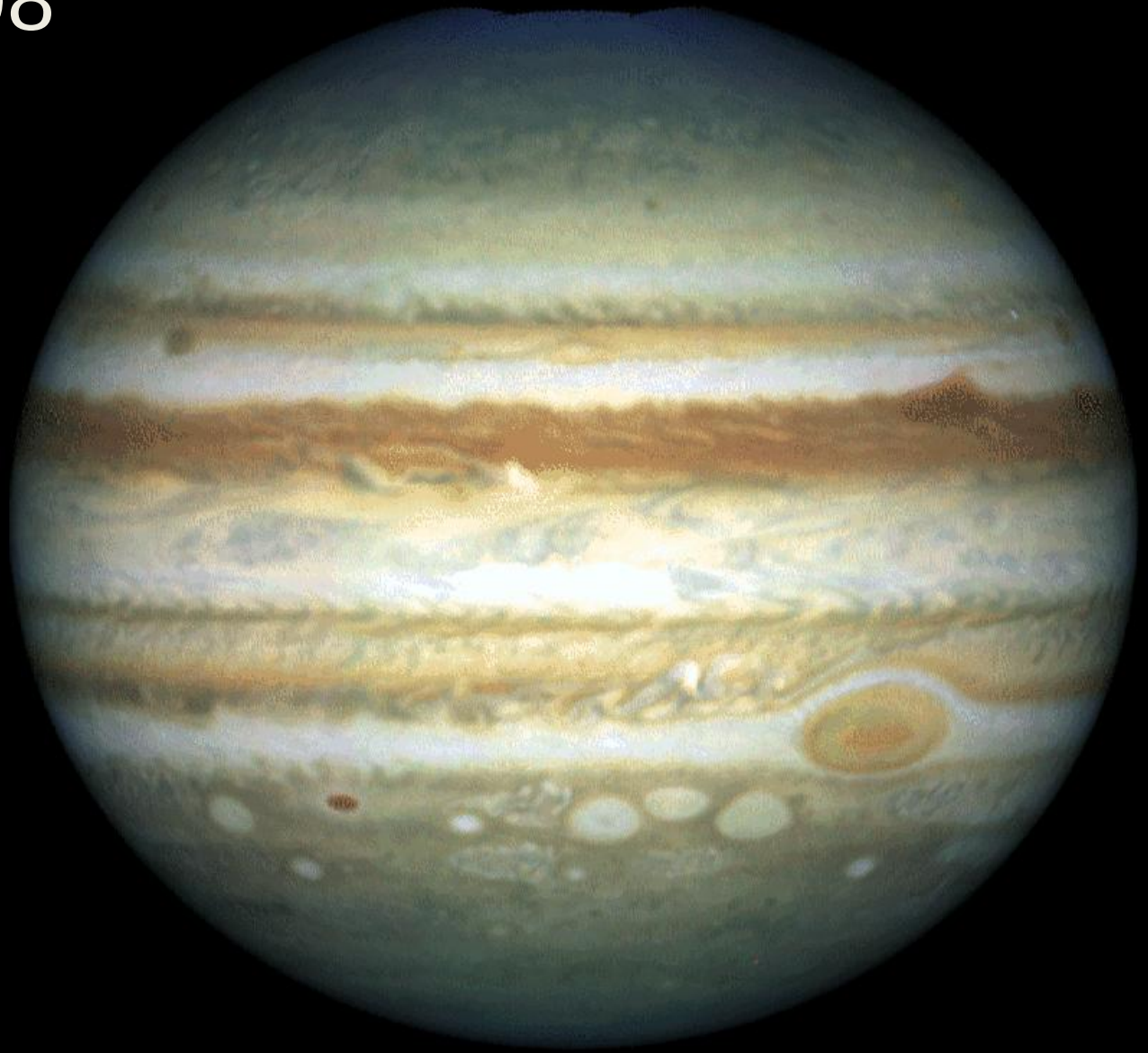
Climate Change on Jupiter

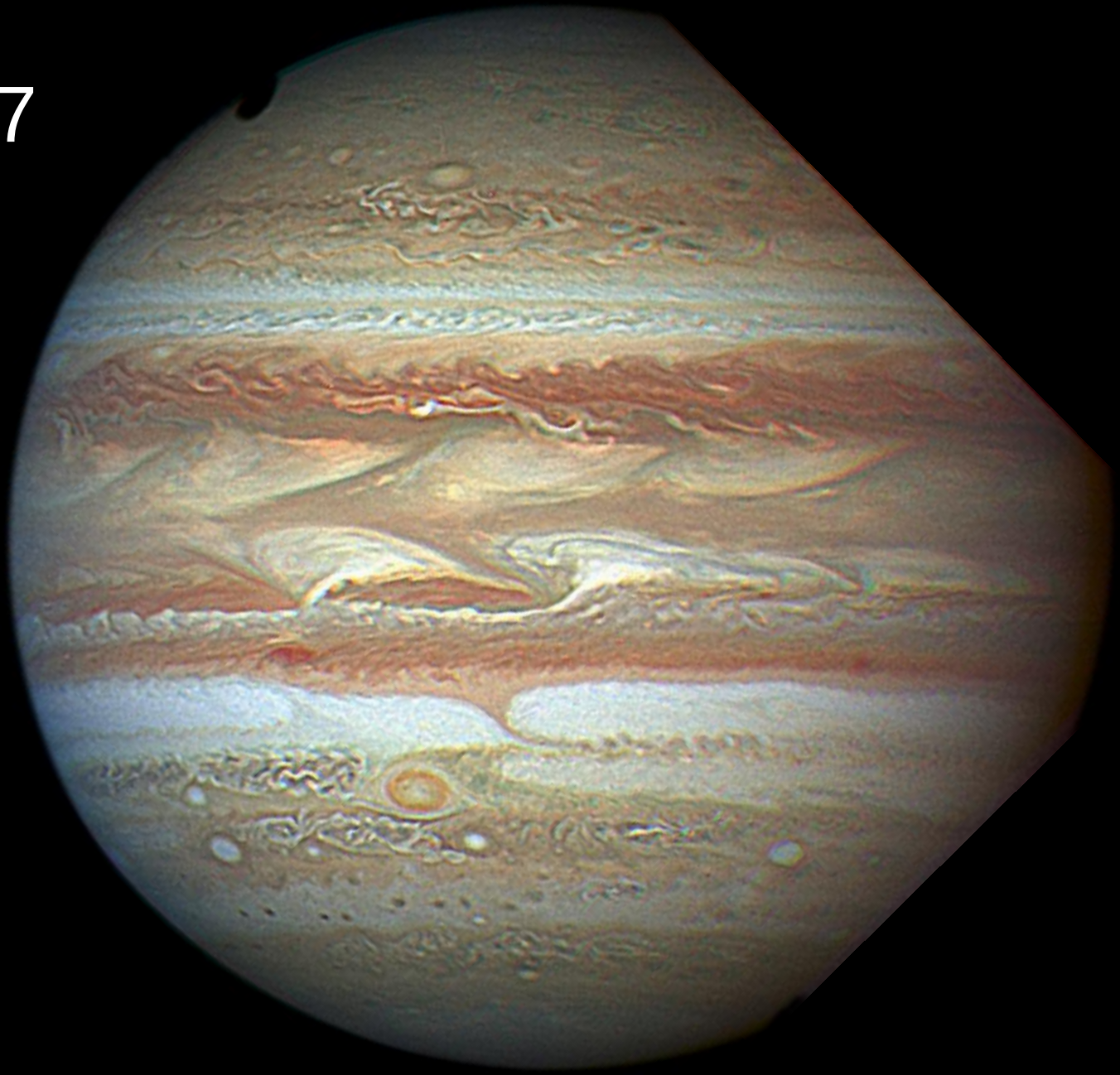
Philip Marcus
University of California at Berkeley



1998



2007



Climate Change on Jupiter?

- Starting in 2001 we began publishing claims that Jupiter would have a significant climate change
- Predicted first observable consequences would be seen in 2006
- Temperature changes of 10^{o} or more

A Change From What?

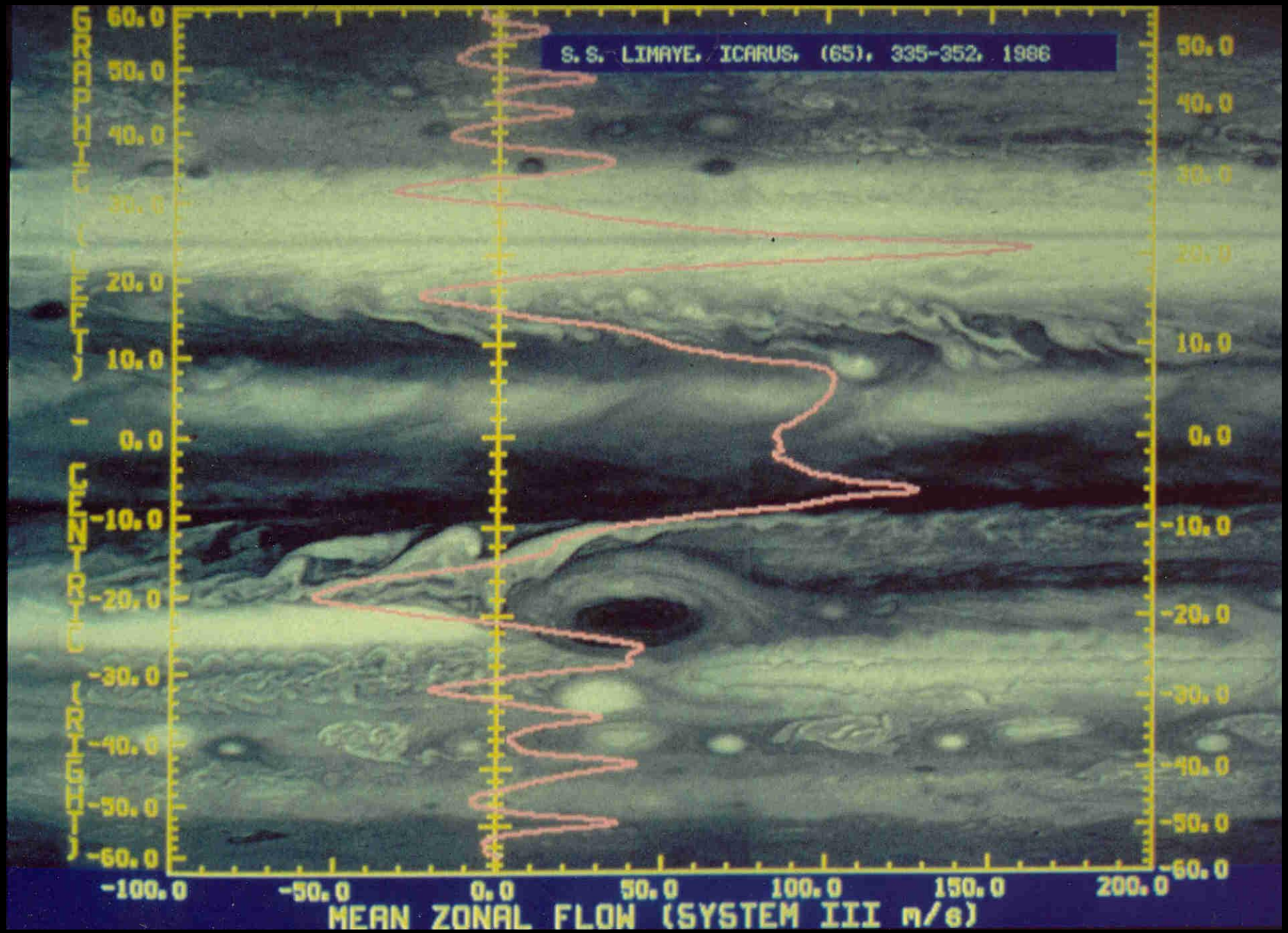
- Our general picture of Jupiter is from the era of the Voyager fly-bys in the late 1970's
- In agreement with ground-based telescope photographs
- Hints of change from *Galileo* and *Hubble* observations

Jet Streams, Vortices & Turbulence

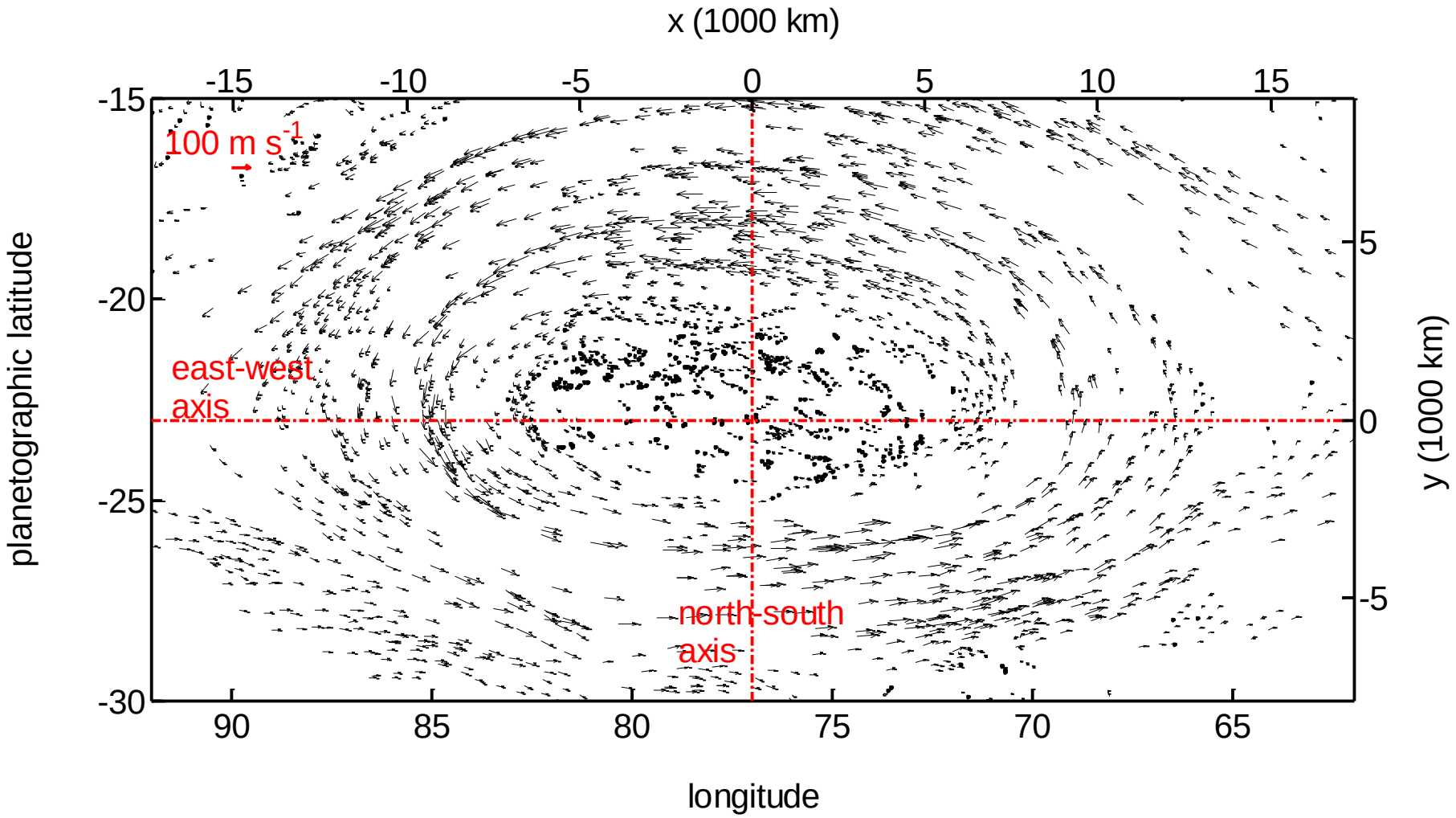
- 12 Eastward-going and 12 Westward-going jet streams ~50-100m/sec
- Long-lived vortices
  - Red Spot, 3 White Ovals
  - 90% are Anti-Cyclones
- Turbulence is ~2 m/sec

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?

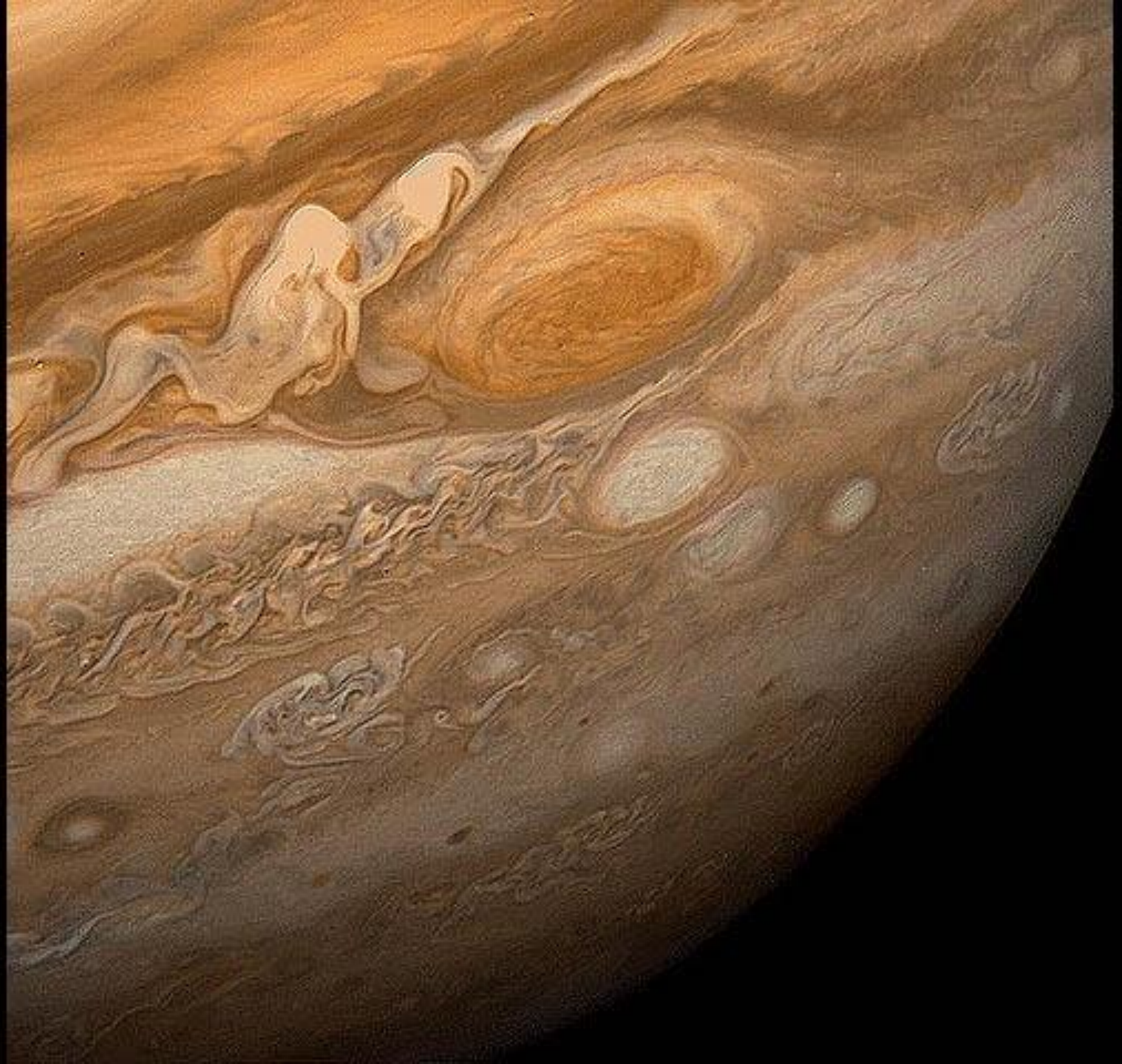

S. S. LIMAYE, ICARUS, (65), 335-352, 1986
GRAPHIC LATITUDE (NORTH)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
MEAN ZONAL FLOW (SYSTEM III m/s)

“By hand” Velocity Extraction



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).



Quasi-geostrophic

Stream function ψ

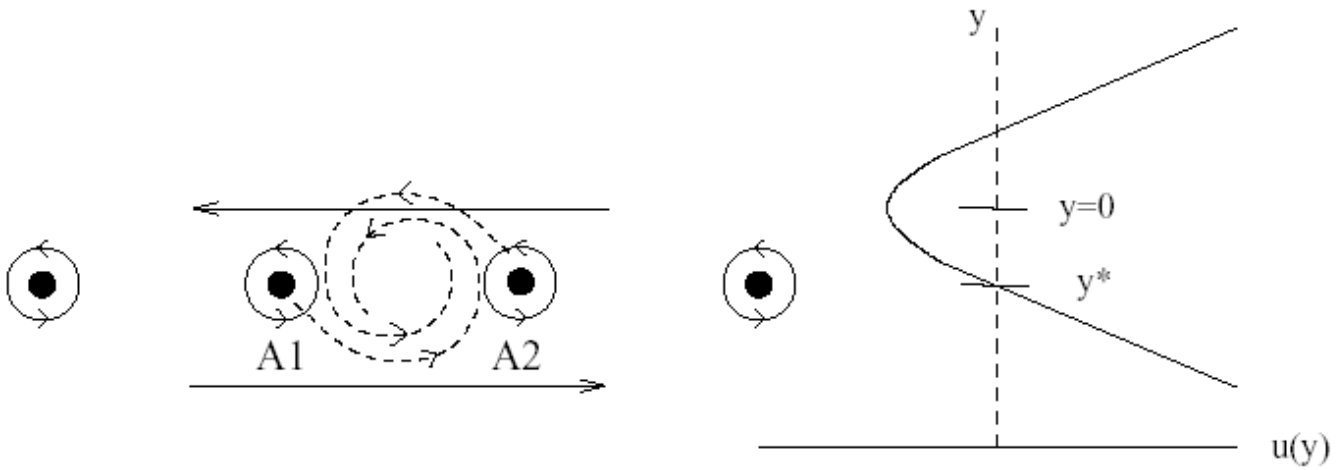
Potential vorticity $q \equiv \nabla^2\psi - \psi/L_r^2 + \beta\, y + \psi_{bottom}(y)/L_r^2$

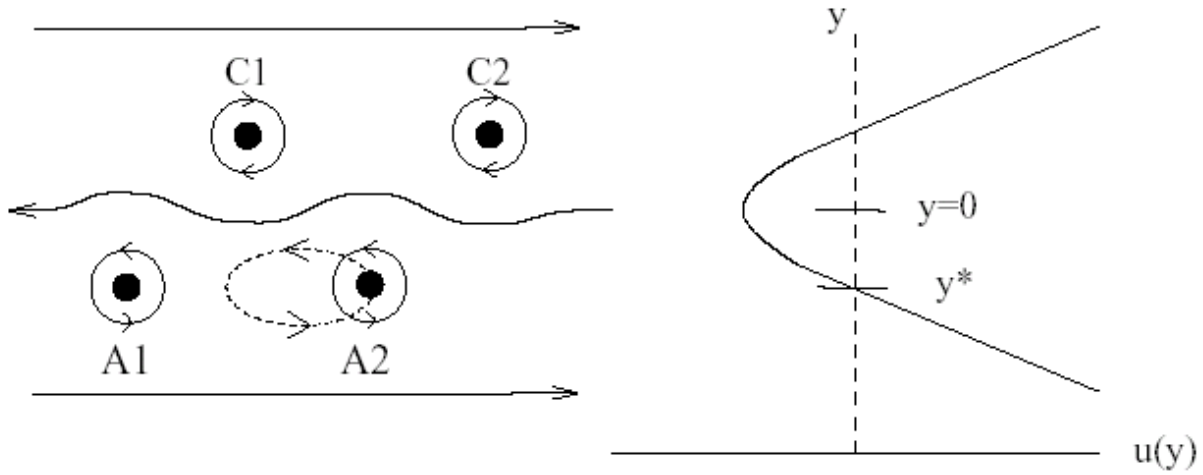
Vorticity $\omega = \nabla^2\psi$

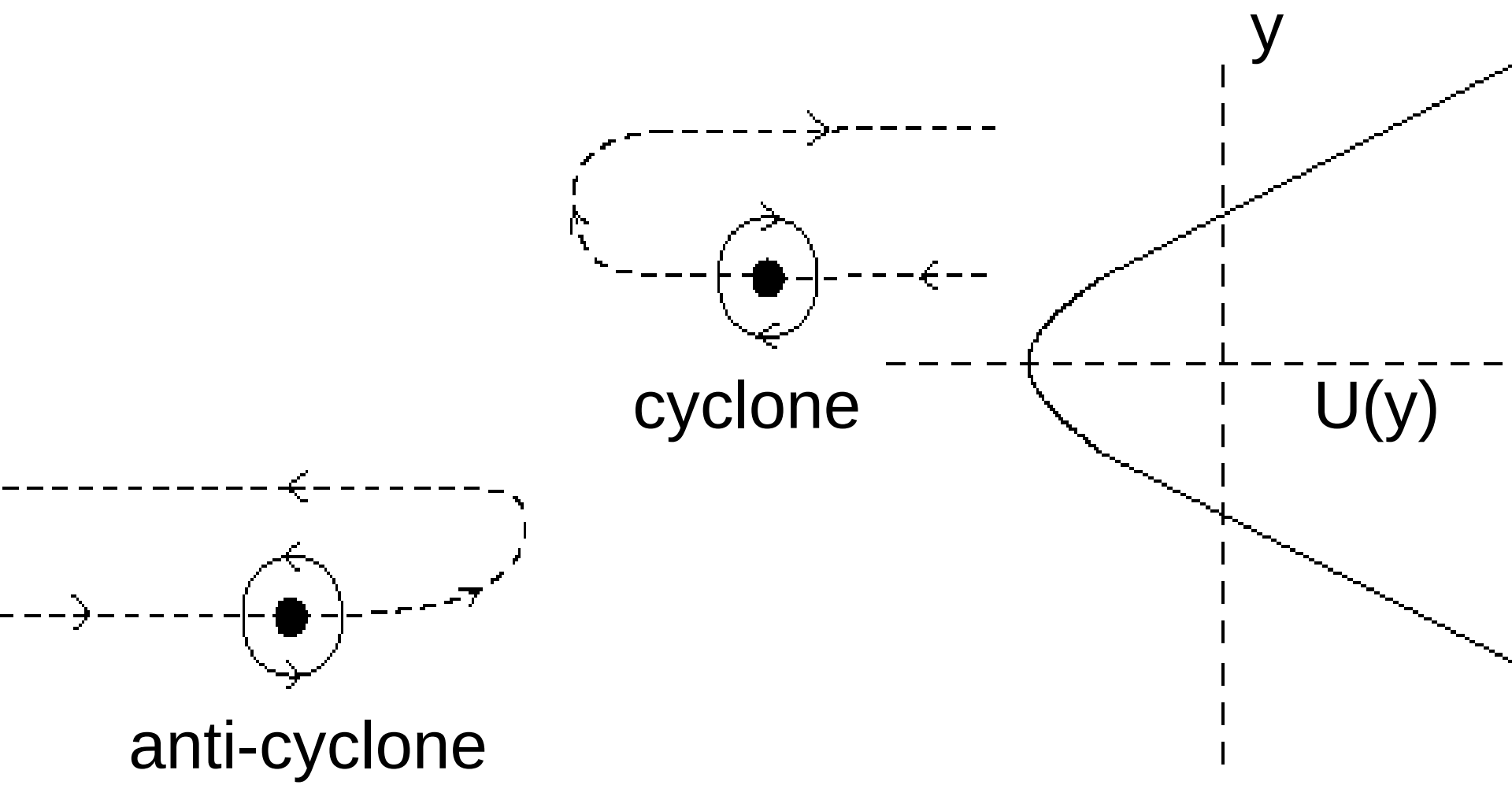
Rossby deformation radius $L_r \equiv (N/f)\, H$ (2000 km)

Vertical pressure scale height H (30 km)

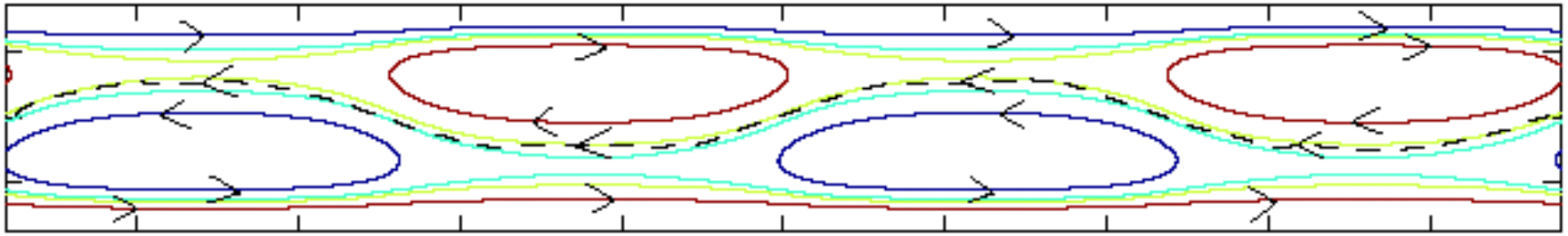
$$D\, q\, /D\, t = 0$$

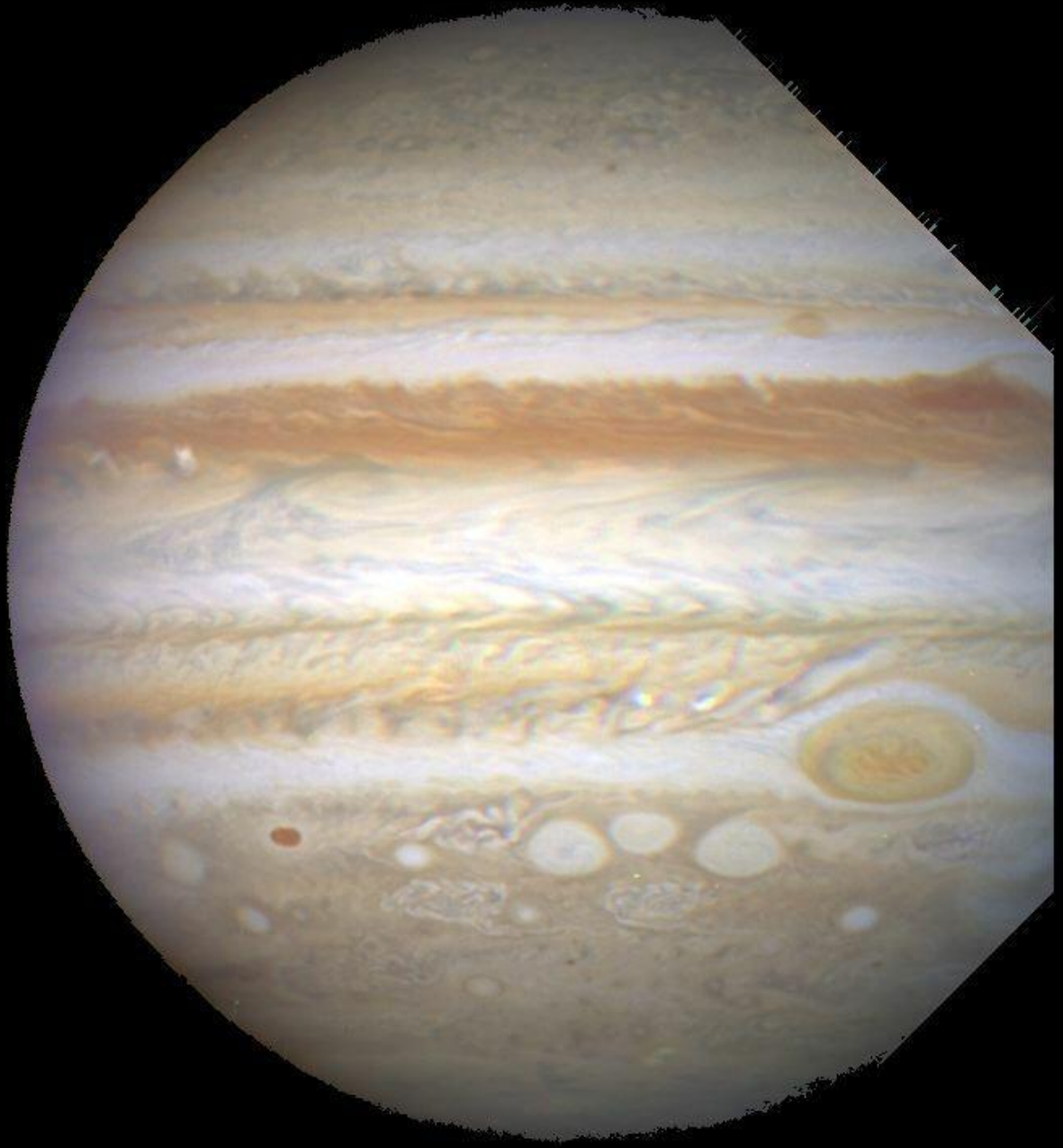

y
y=0
y*
A1
A2
u(y)

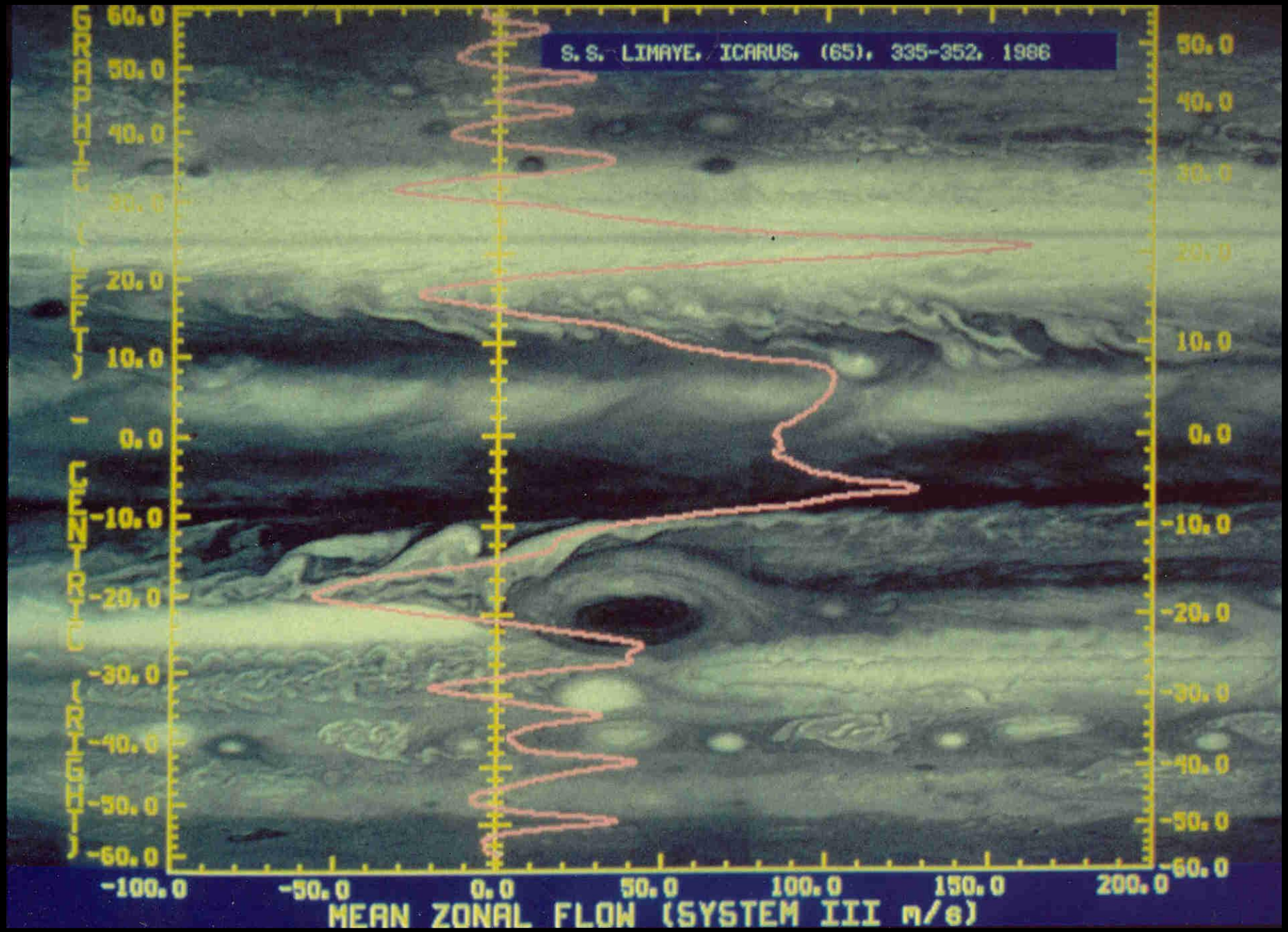

C1
C2
A1
A2
y
y=0
y*
u(y)


y
cyclone
U(y)
anti-cyclone

Only One Great Red Spot



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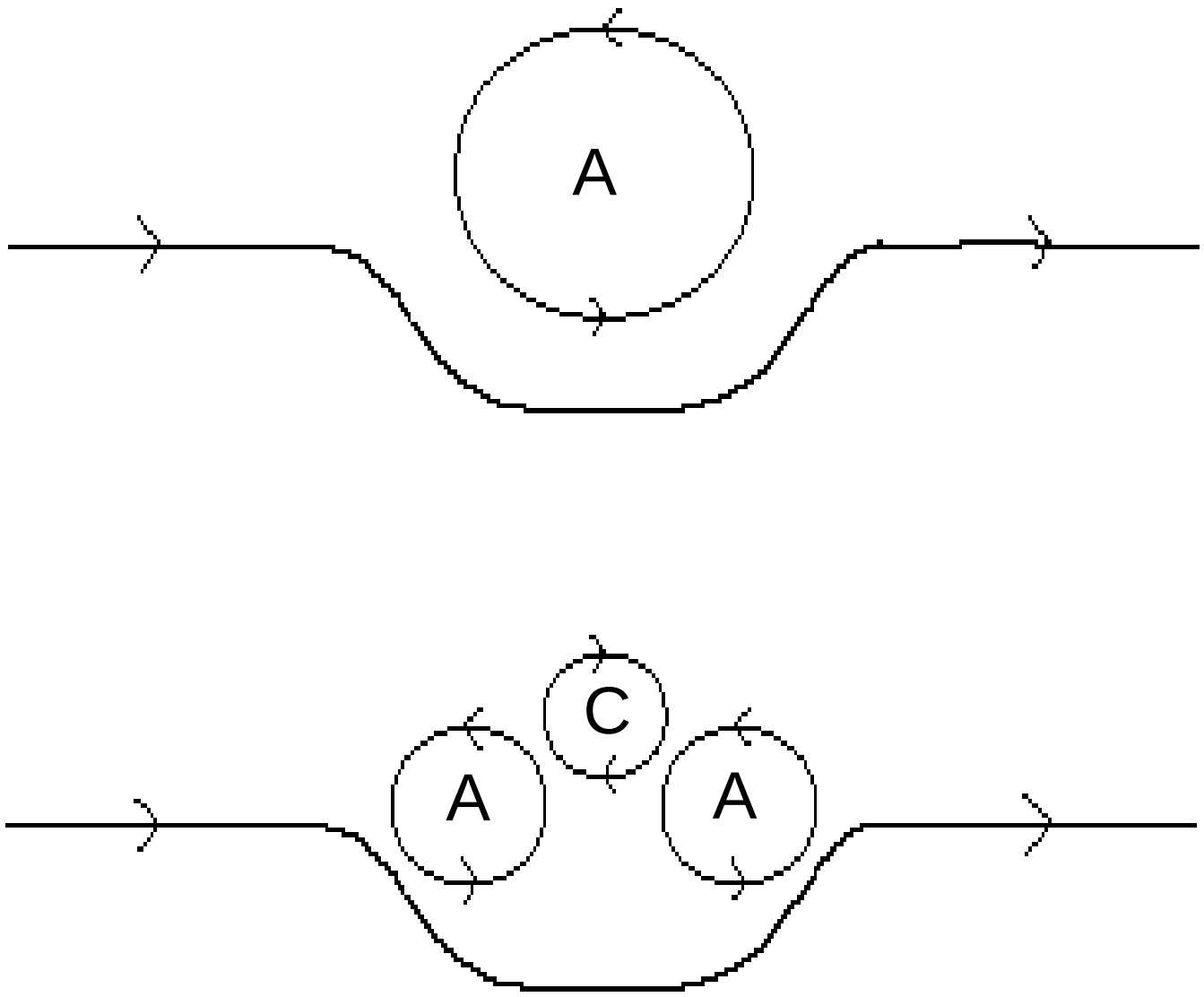
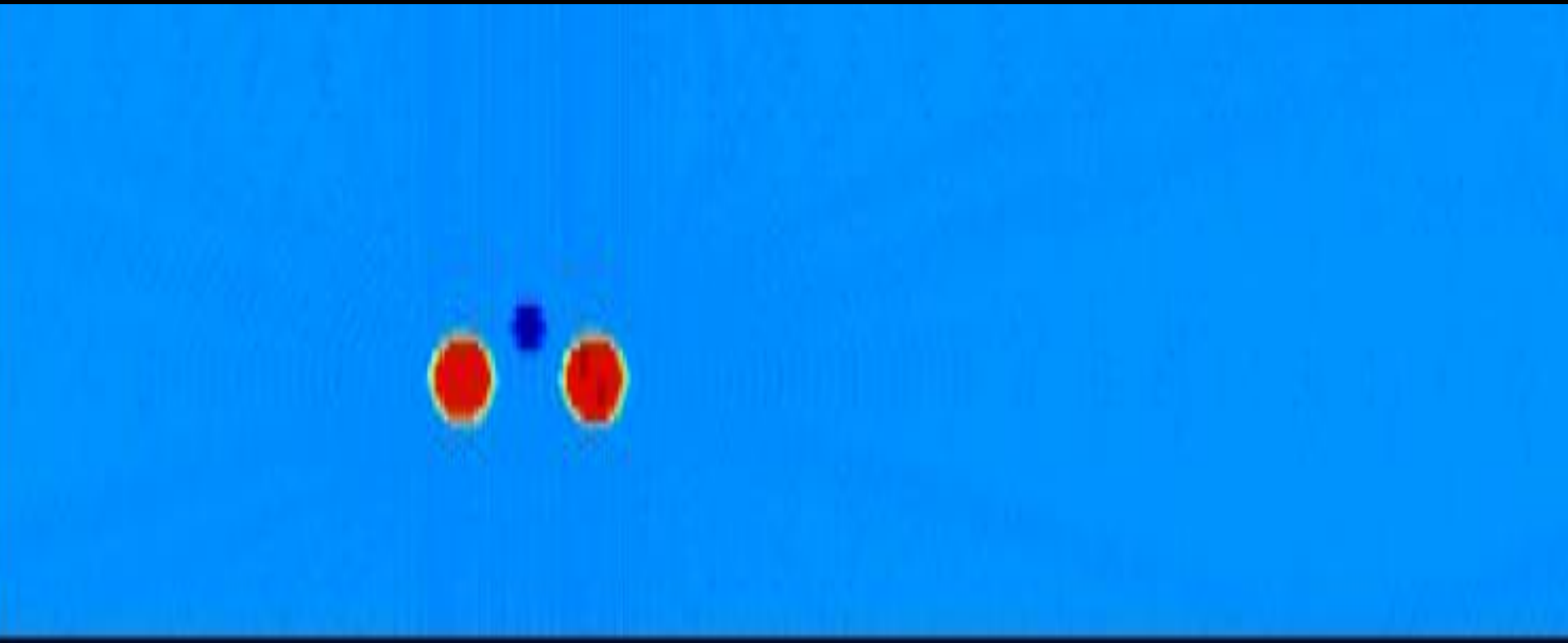
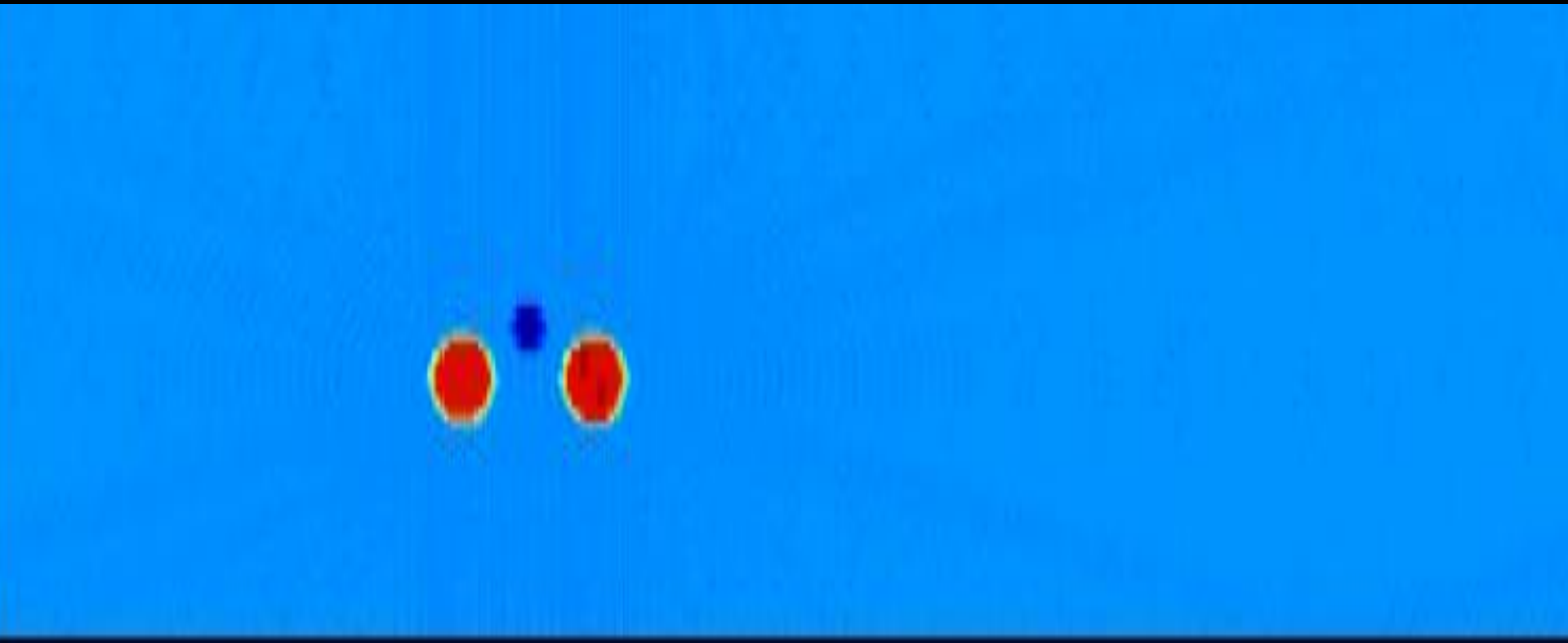
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0
-50.0
0.0
50.0
100.0
150.0
200.0
MEAN ZONAL FLOW (SYSTEM III m/s)

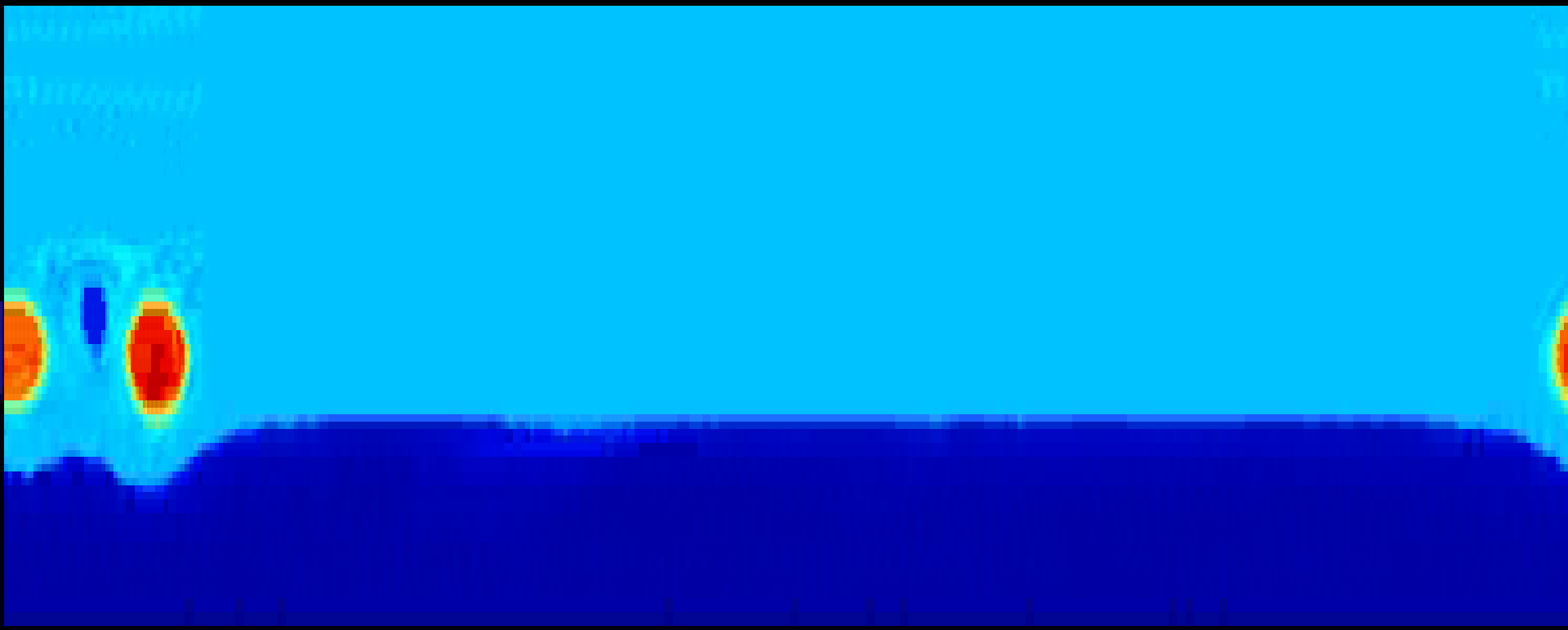

Jet Stream
Monday
Oct 08, 2007
C
01 Oct 2007 17:03 GMT / 01 Oct 2007 01:03 PM EDT

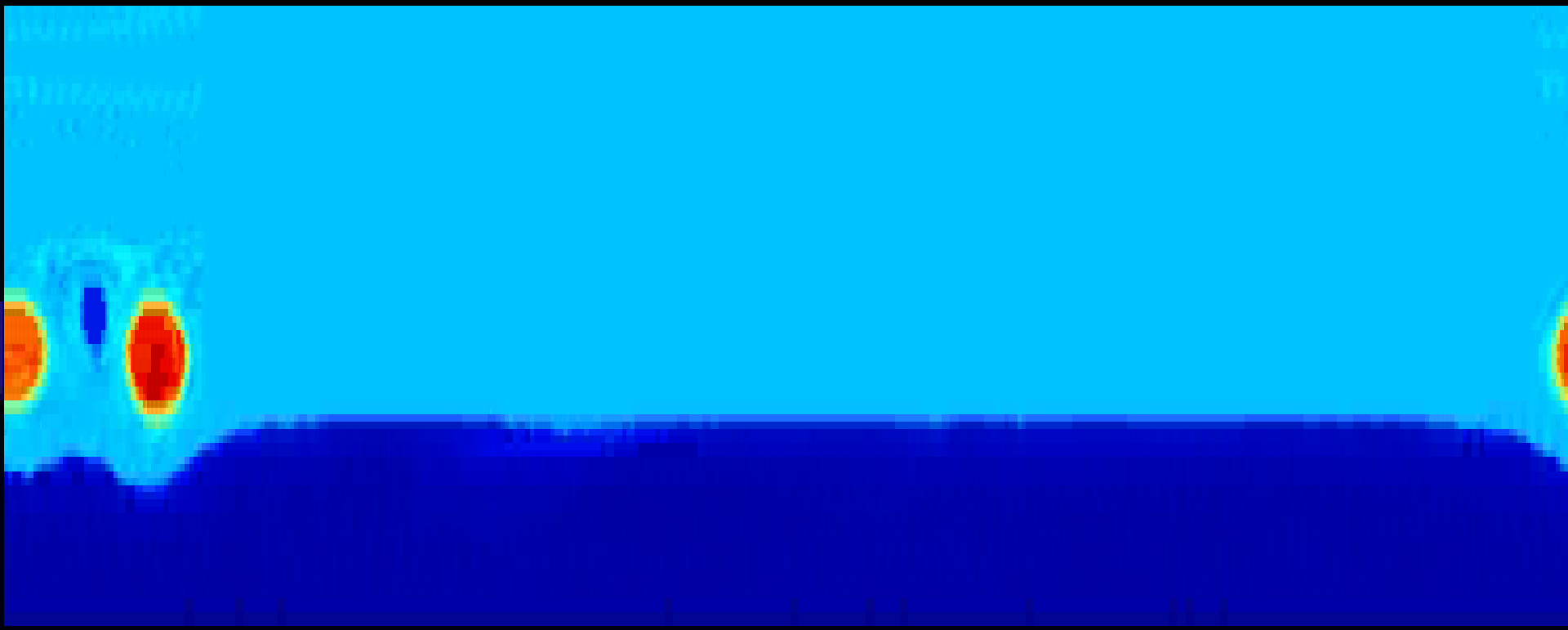


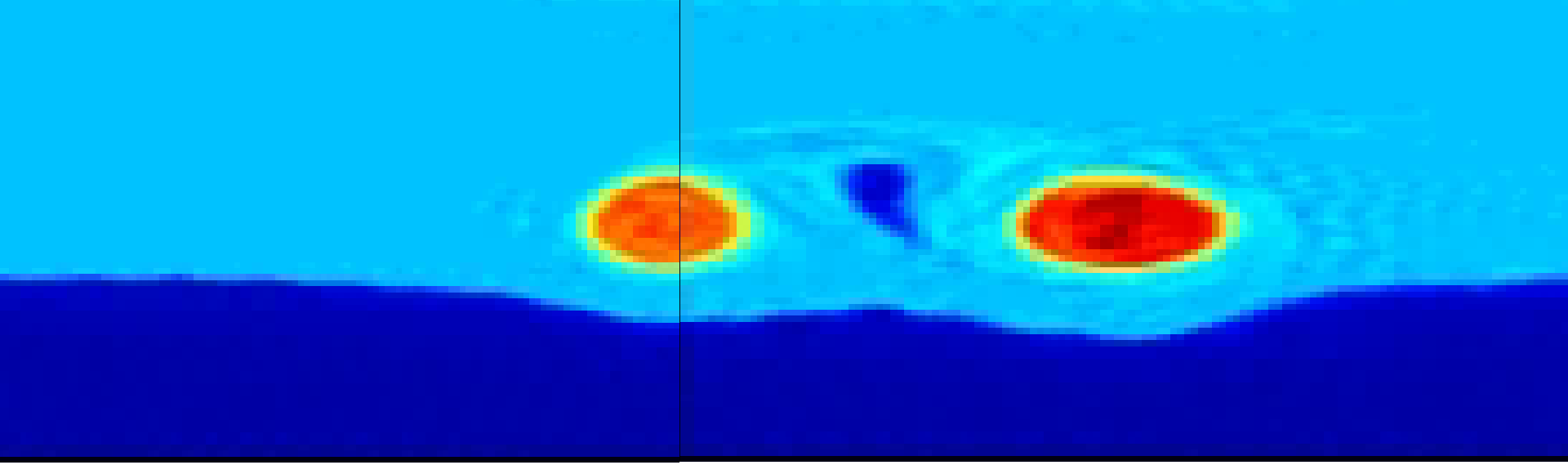
Cyclone below critical value

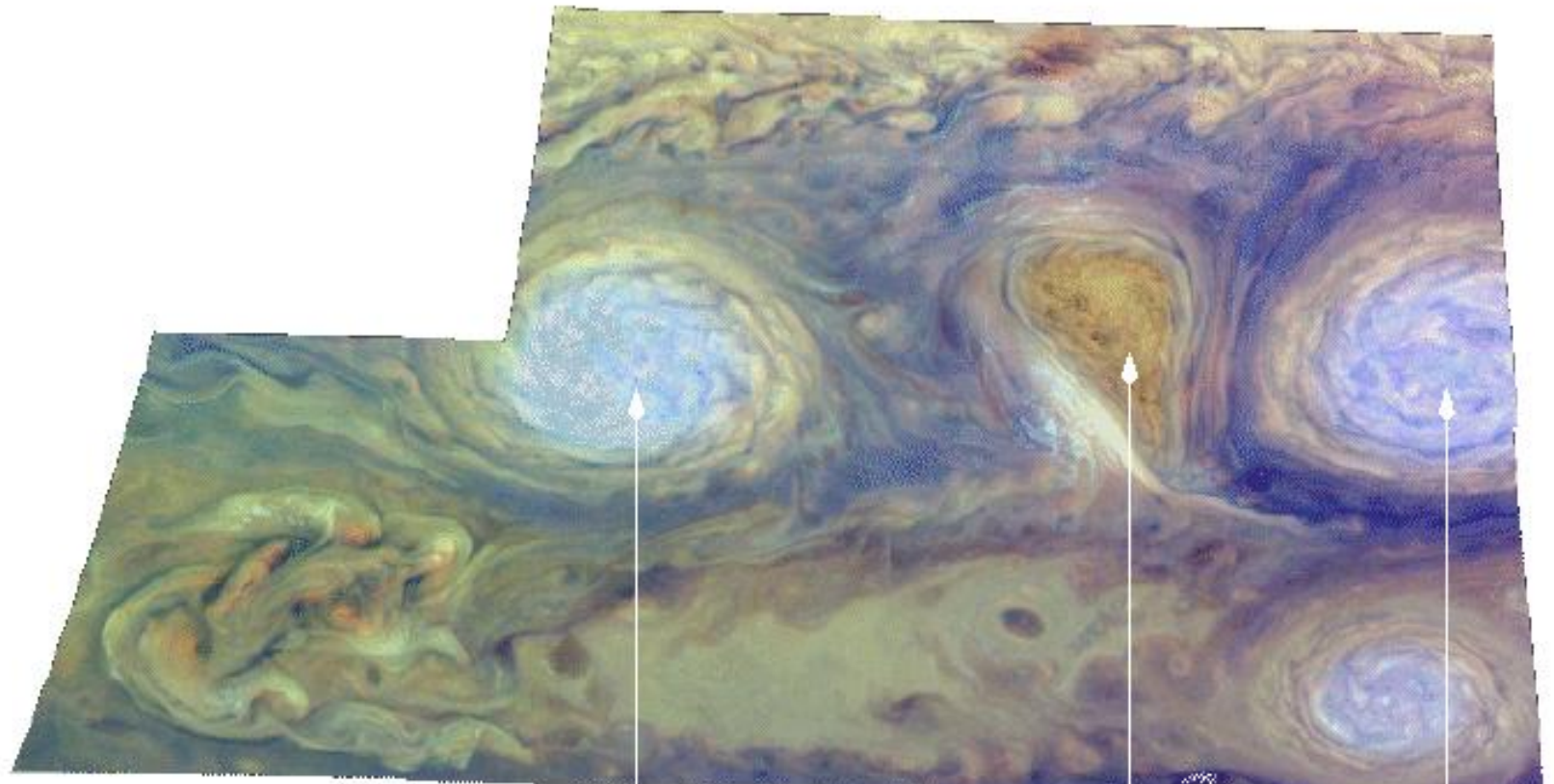


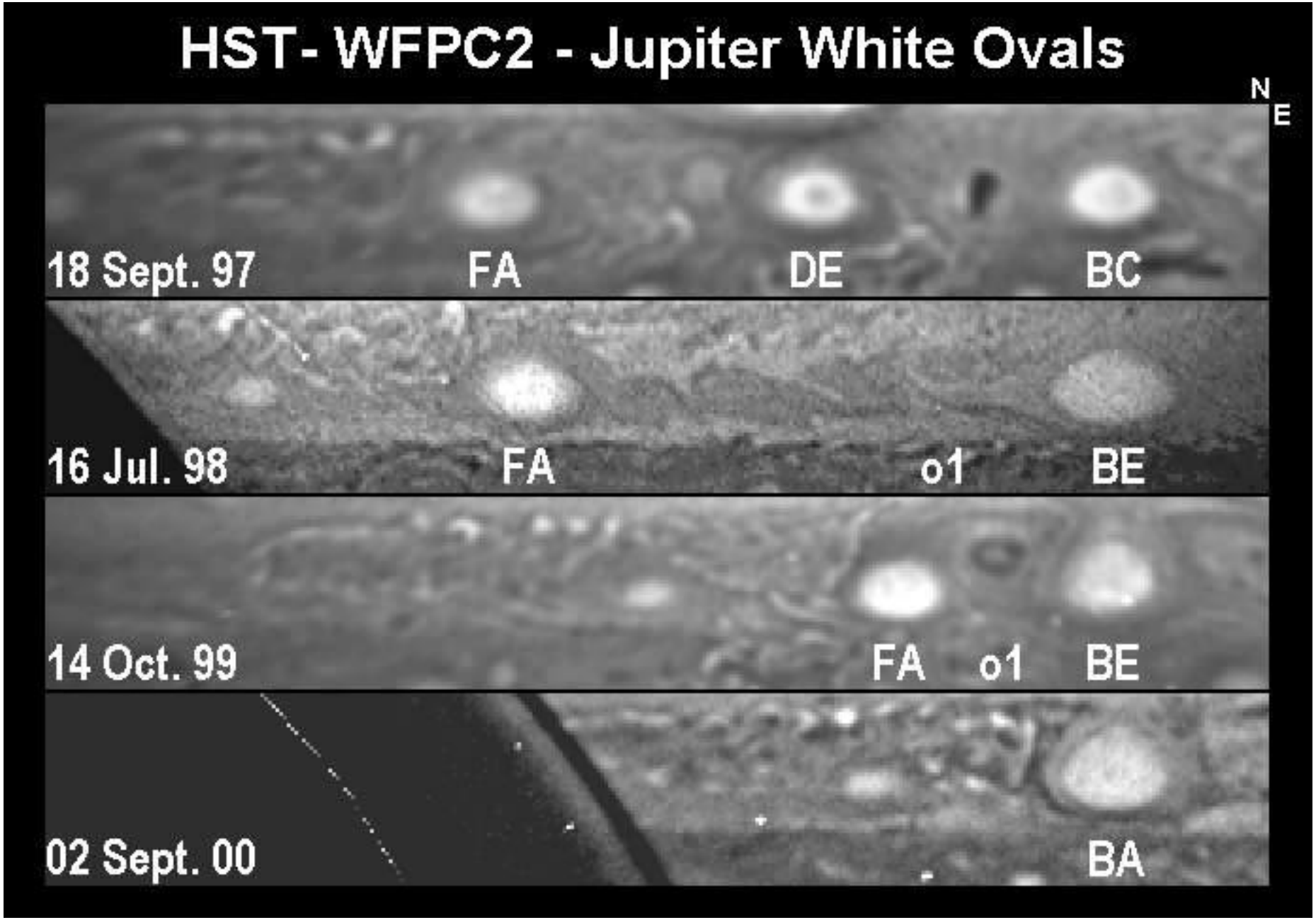


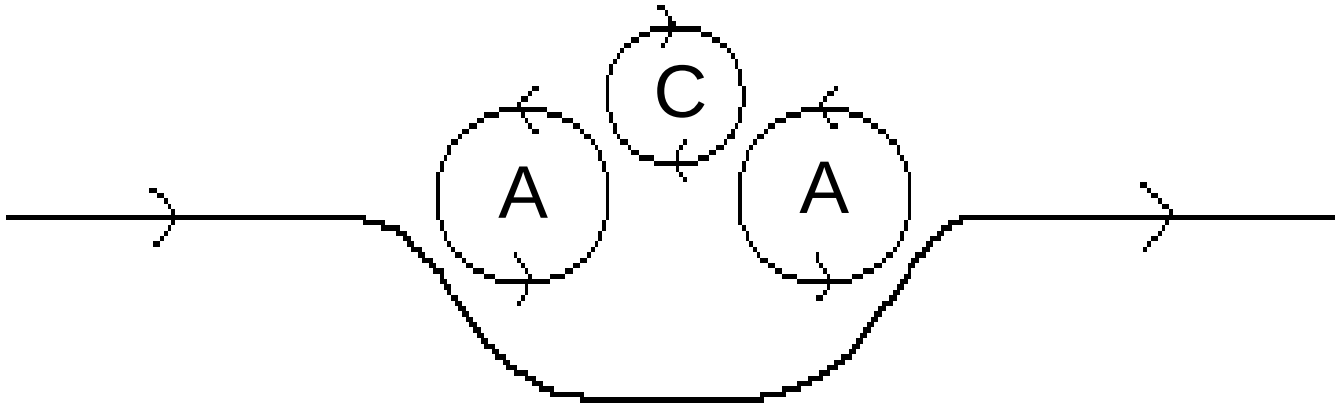




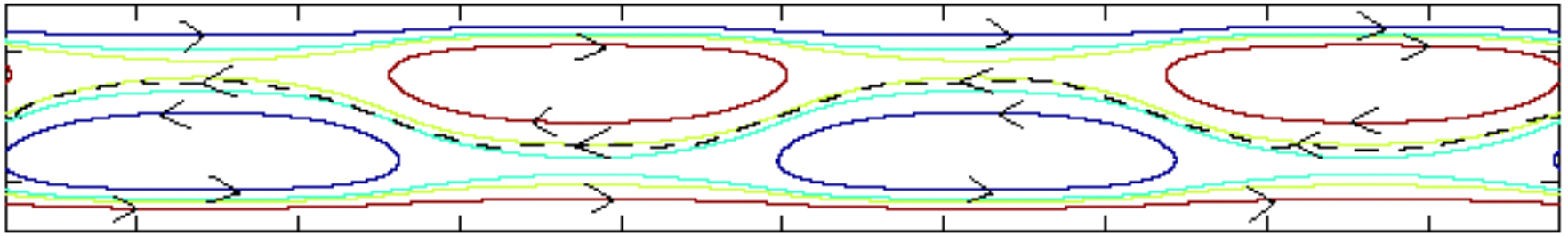





HST- WFPC2 - Jupiter White Ovals
N
E
18 Sept. 97
FA
DE
BC
16 Jul. 98
FA
o1
BE
14 Oct. 99
FA
o1
BE
02 Sept. 00
BA


C
A
A

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



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)

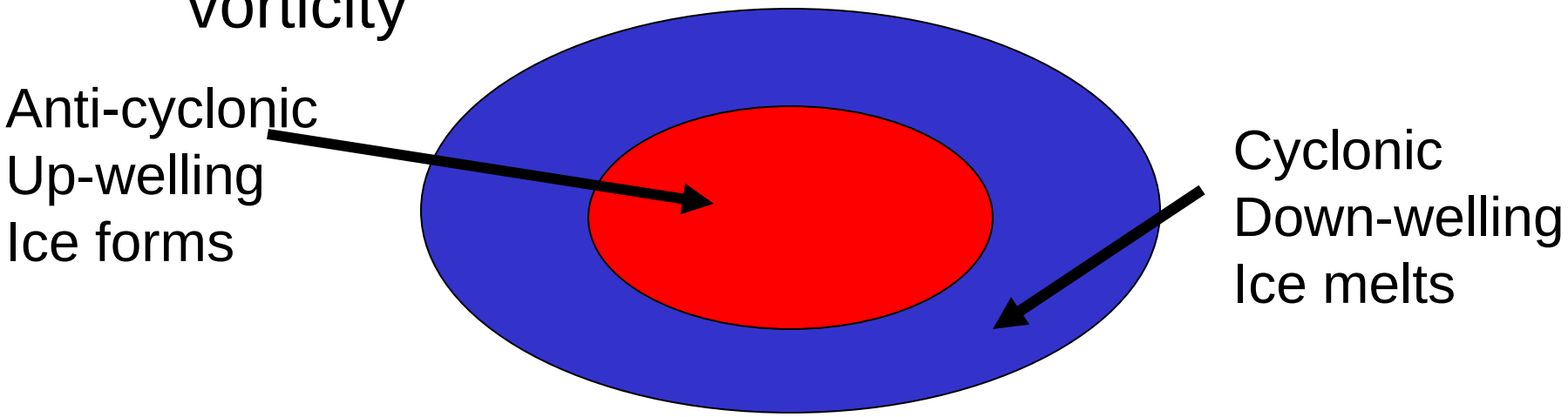
Streamlines are not particle pathlines

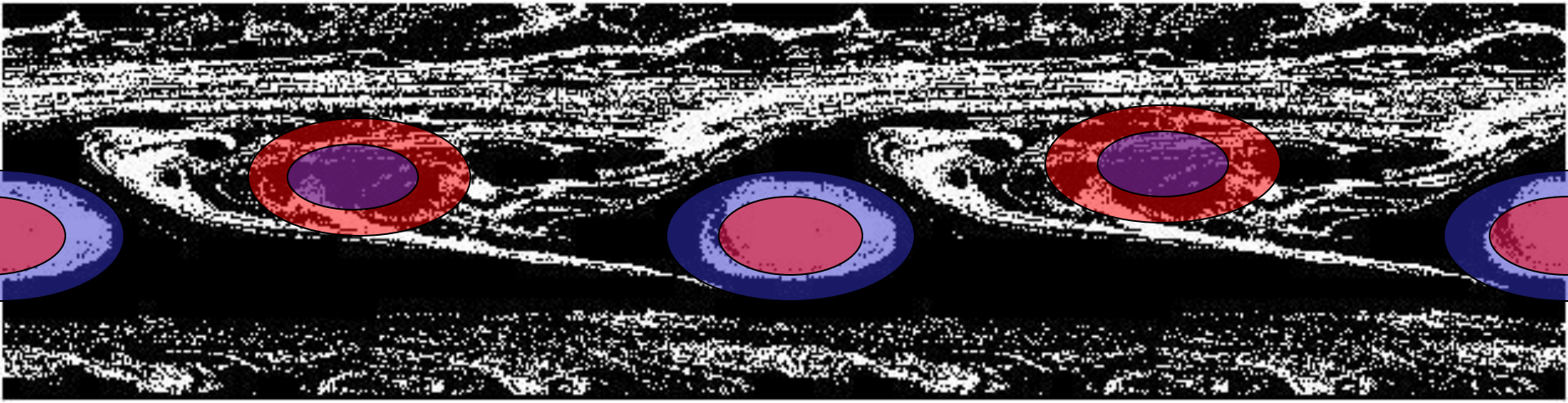
- Clouds are NH_3 ice crystals
- Created with cooling, destroyed with warming
- Due to 3D secondary flow:
  - Anti-cyclonic regions have upwelling
  - Cyclonic regions have down-welling
- In a sub-adiabatic atmosphere upwelling cools the flow

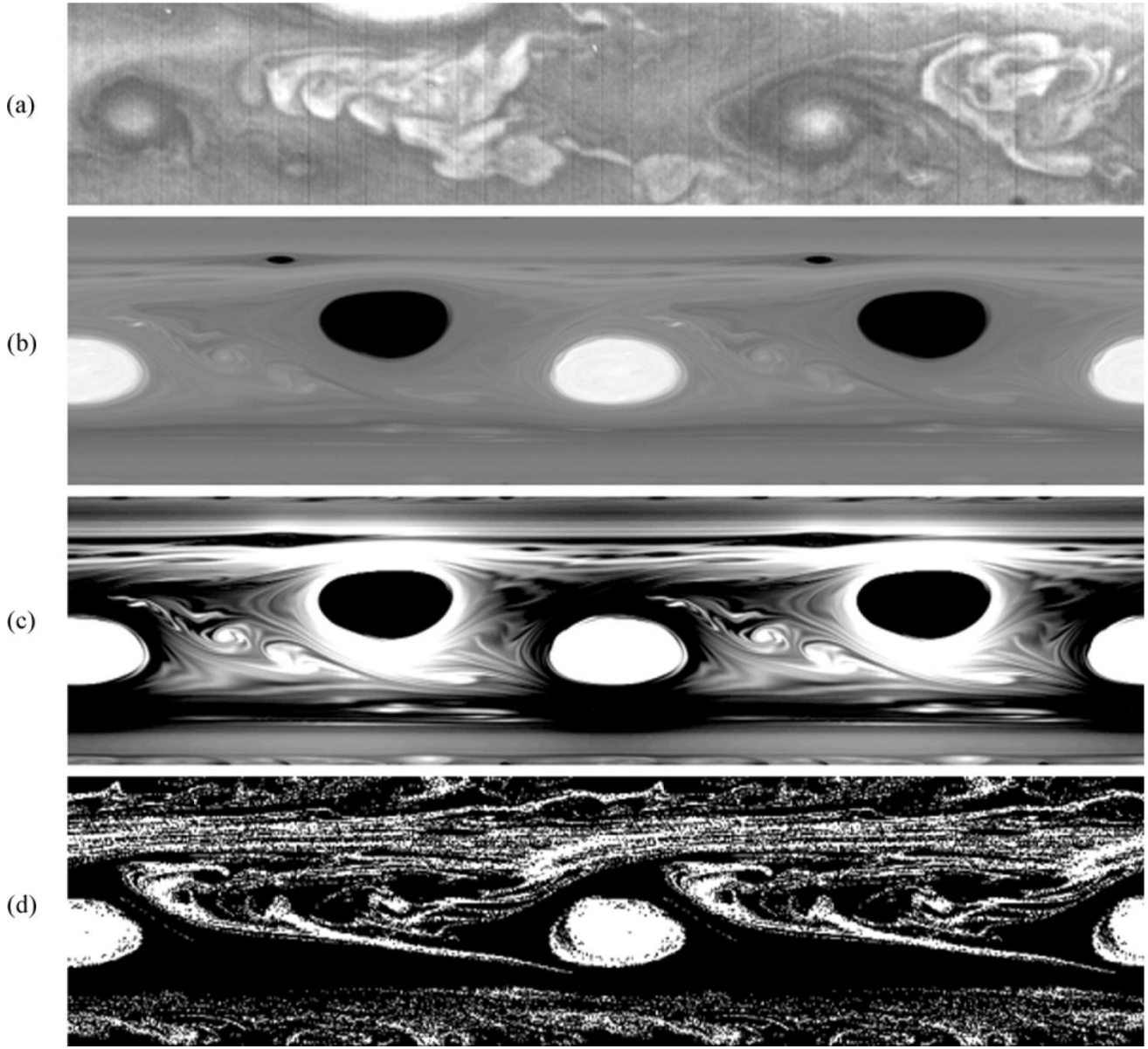
“Anti-cyclone” refers to the potential vorticity

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

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

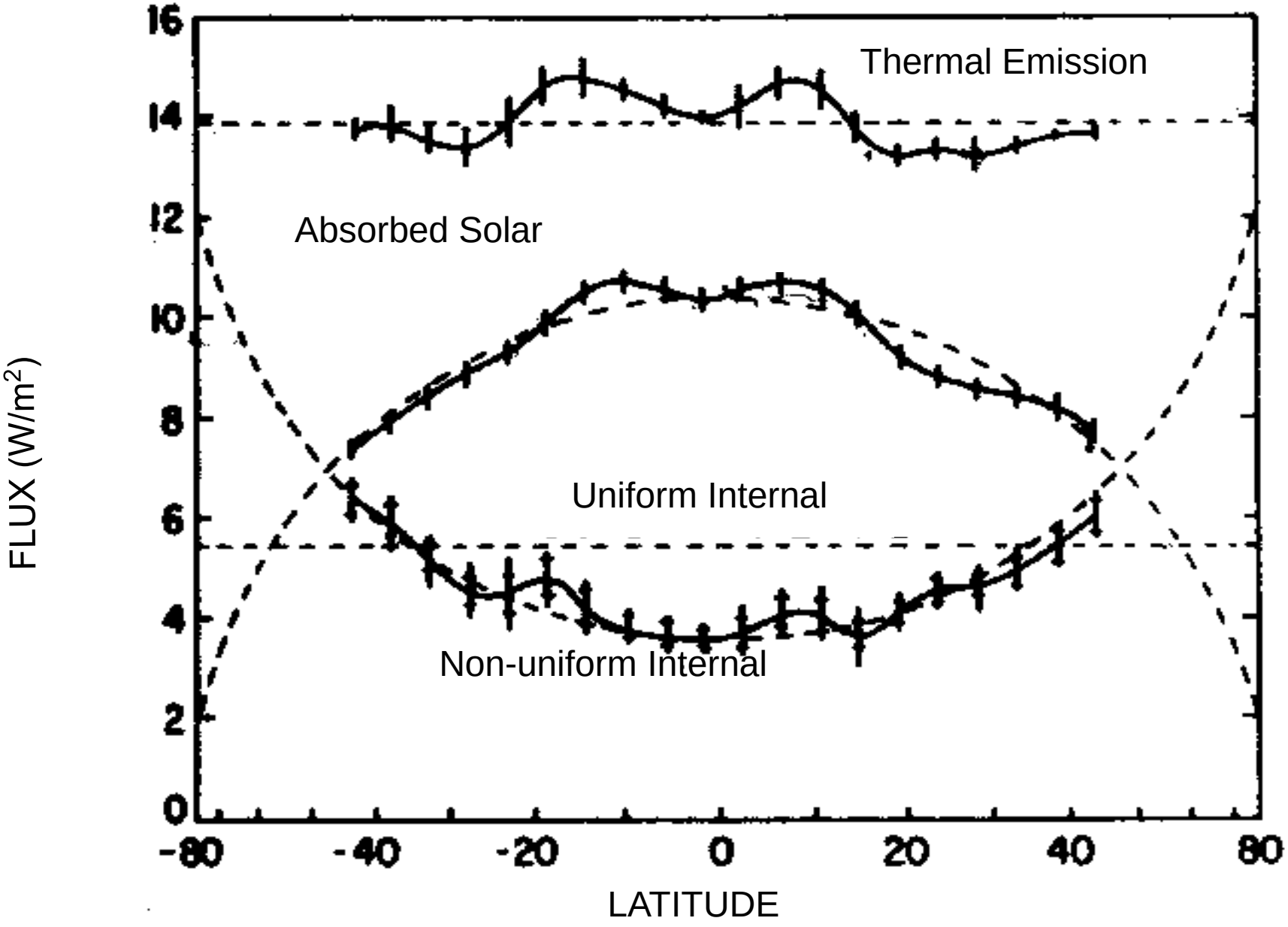





(a)
(b)
(c)
(d)

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 $\pm$ 4K. least half of the heat deposited from the Sun is captured and absorbed in the cloud layer

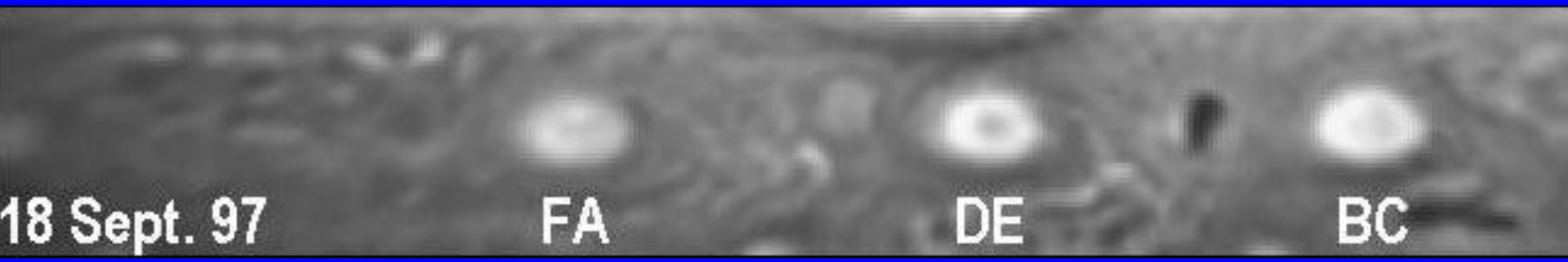

Thermal Emission
Absorbed Solar
Uniform Internal
Non-uniform Internal
FLUX (W/m2)
LATITUDE
16
14
12
10
8
6
4
2
0
-80
-40
-20
0
20
40
80

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

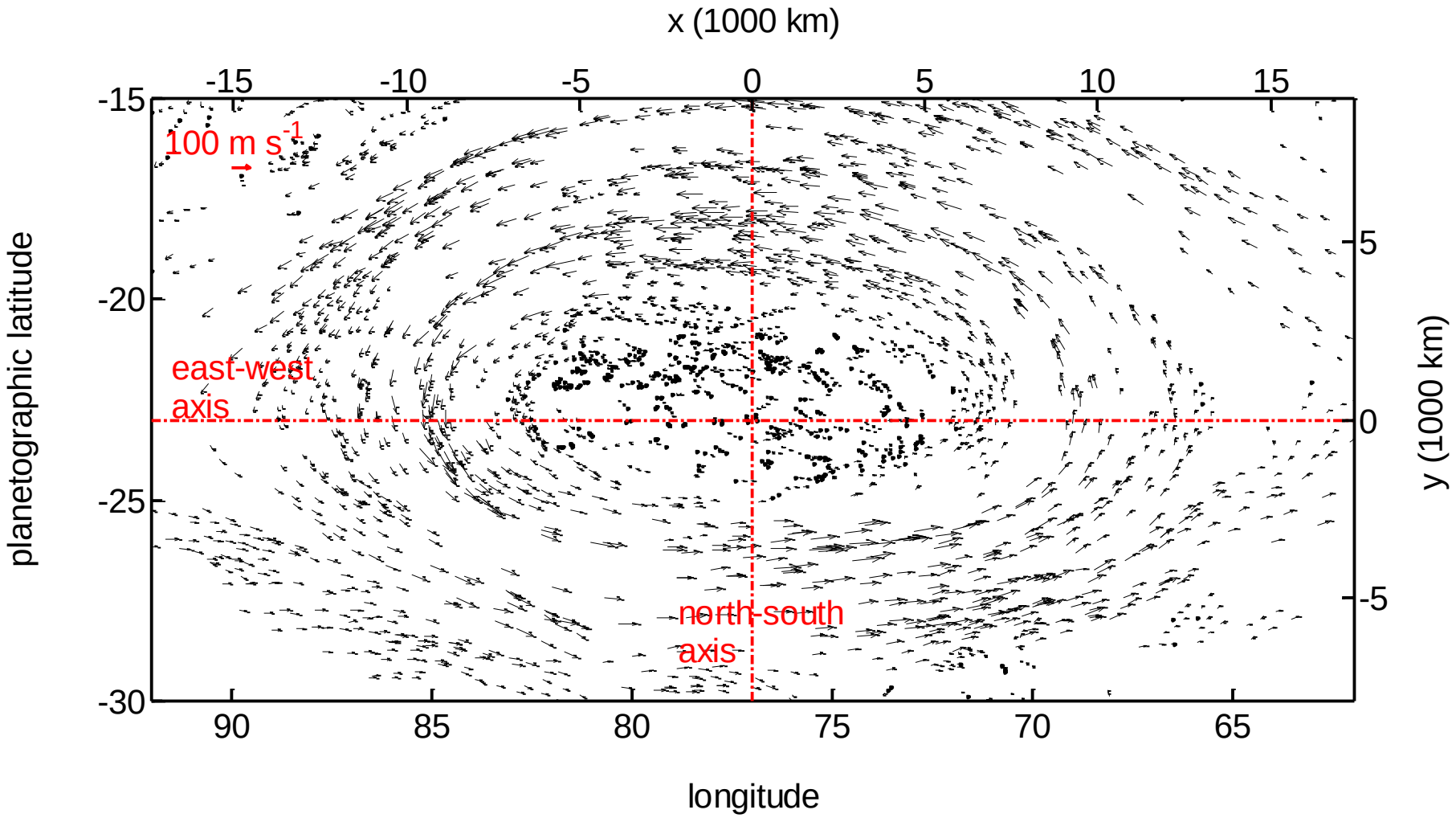
- No space or ground-based telescope since Voyager can measure cloud top temperature
- Limited observations coupled with models would work if there were no clouds.
- Need to infer temperature changes
- But first, let's revisit the measurements of velocities

New Red Oval

The White Oval that formed in 2000
turned red in December 2005

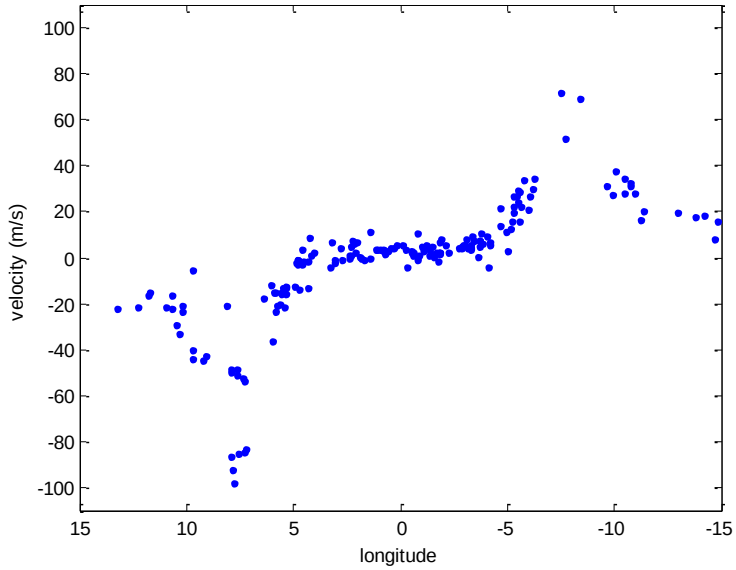
Is this a sign of a change in temperature?

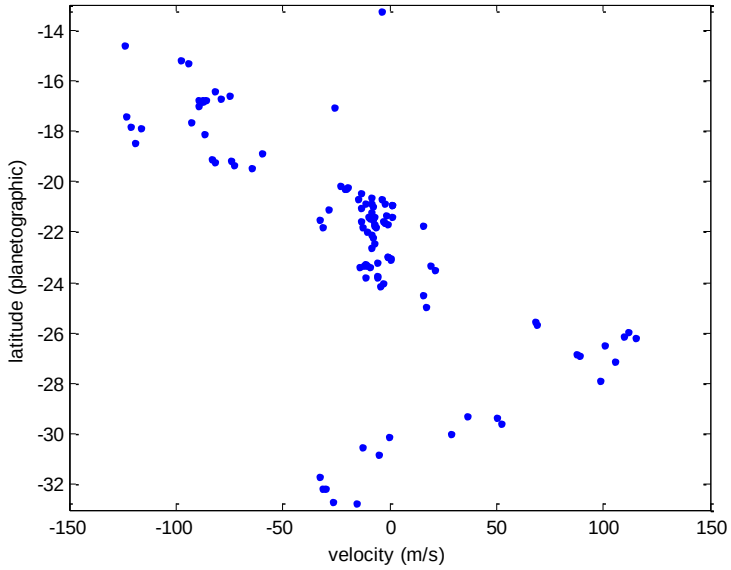
“By hand” Velocity Extraction



Manual Cloud Tracking GRS

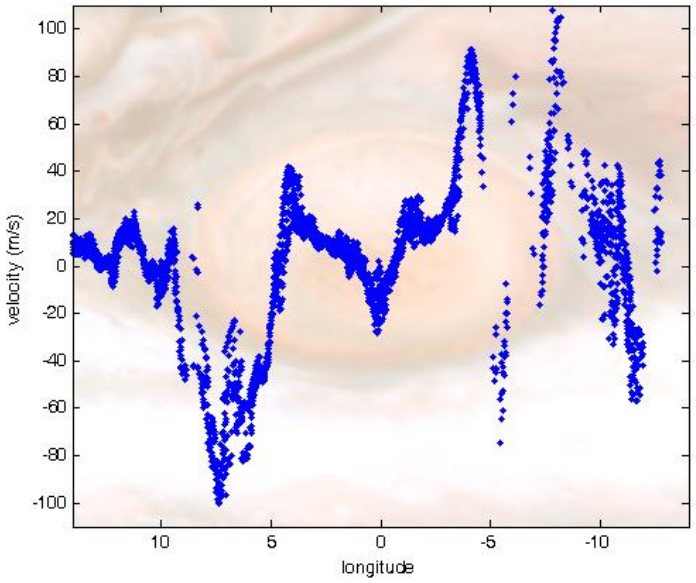
- 10 hours tracks ~10^3 velocity vector
- too few vectors

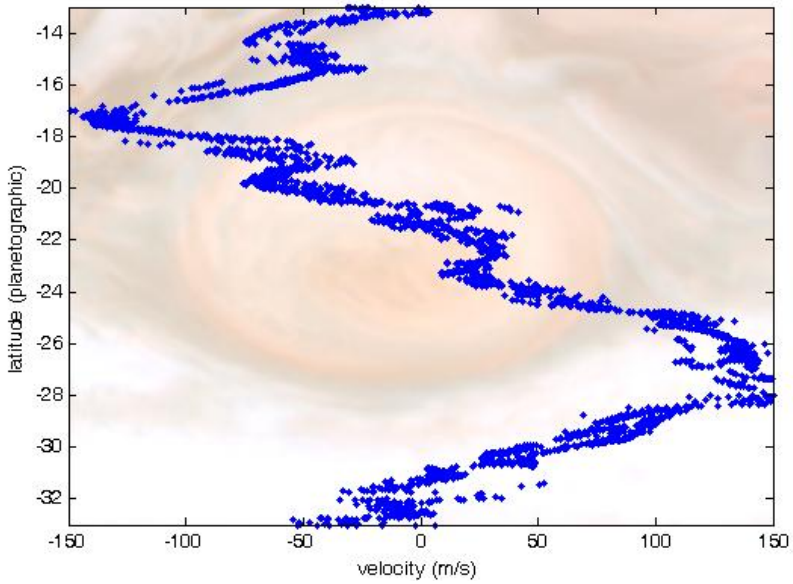




Automatic Methods used in Lab

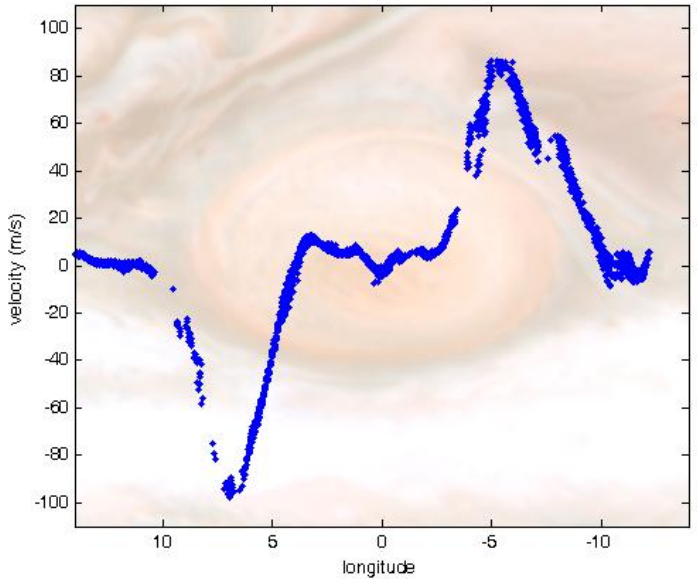
- Cannot track feature of GRS for more than 40 minutes
- ~10^5 velocity vectors; Uncertainty ~32 m/s

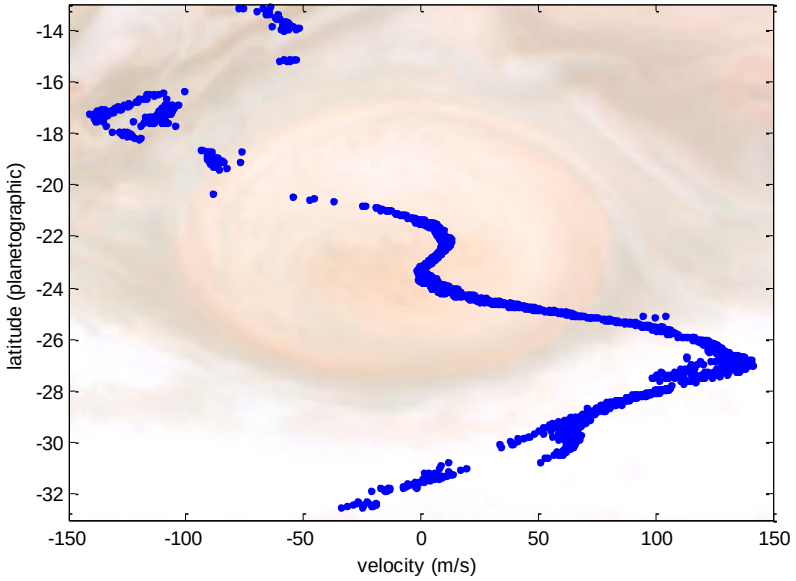




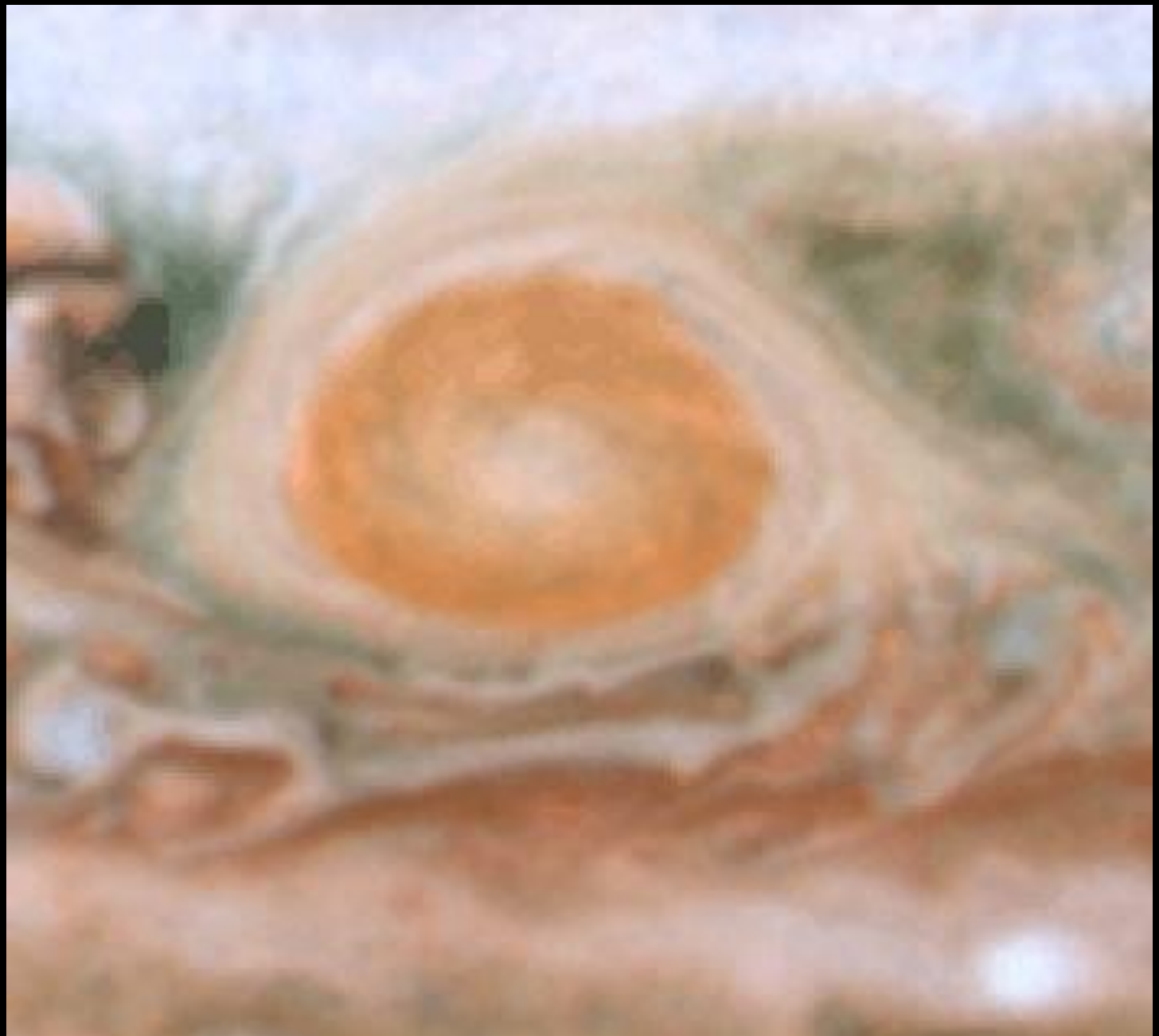
Advection Corrected CIV GRS

- Tracks for 10 hours,~3x10^6 velocity vectors
- Uncertainty ~5 m/s





New Red Oval 10 hours



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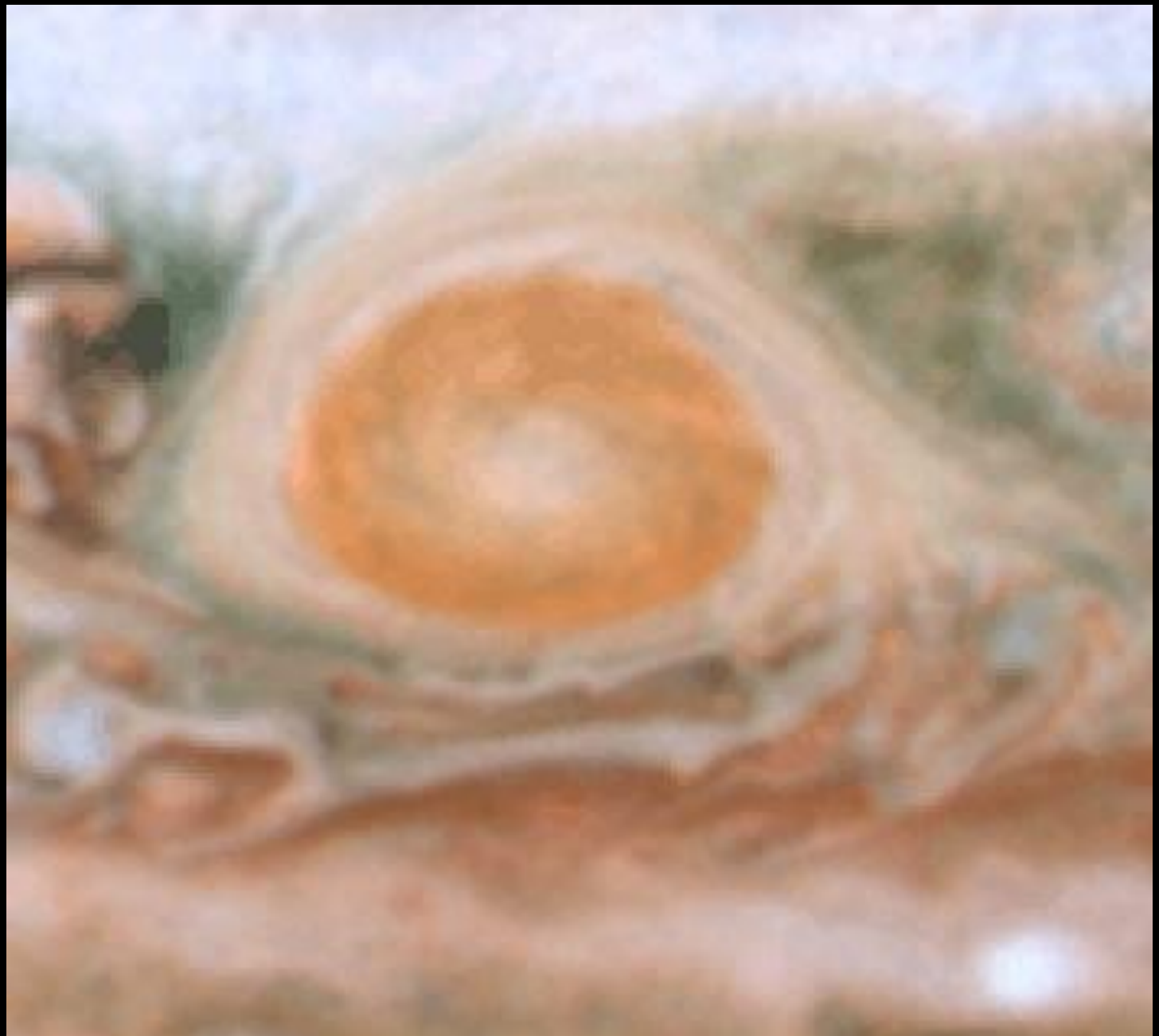
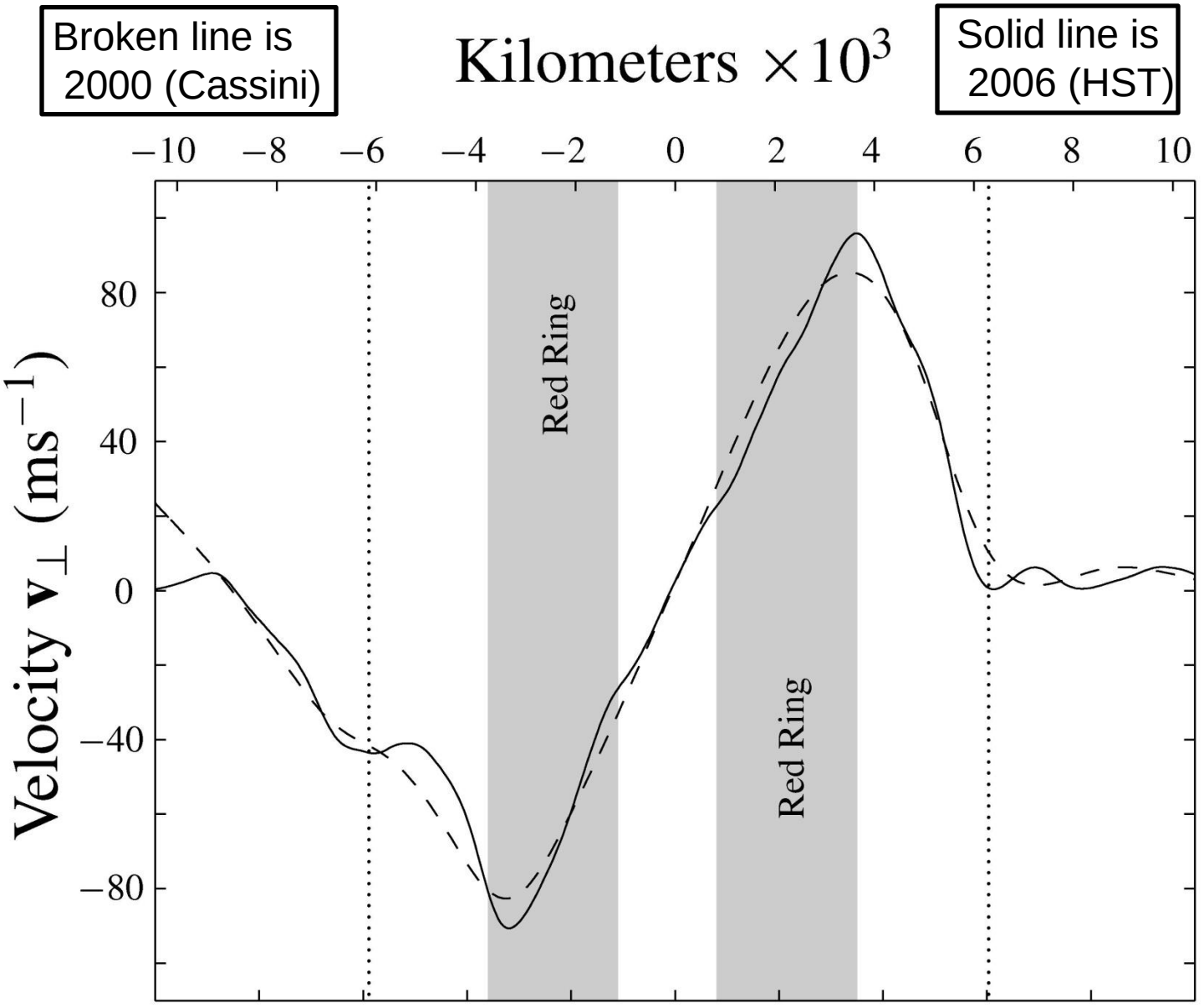


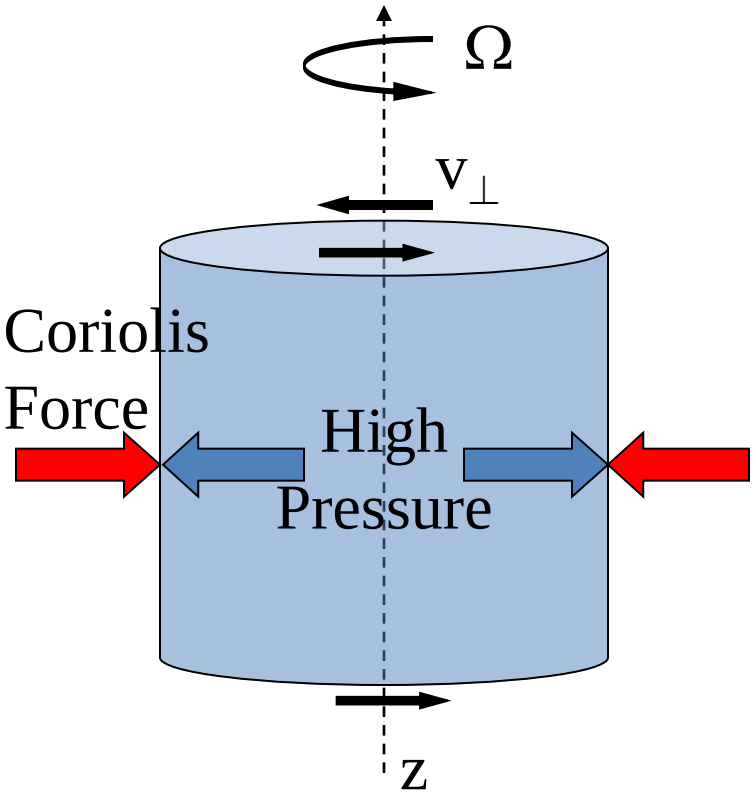

Broken line is
2000 (Cassini)
Kilometers $\times 10^3$
Solid line is
2006 (HST)
−10
−8
−6
−4
−2
0
2
4
6
8
10
80
40
0
−40
−80
Velocity $\mathbf{v}_\perp$ (ms^{-1})
Red Ring
Red Ring

2D Projection At One Elevation

- This 2d slice has not changed, but is that enough to argue that the 3d shape, size and velocity are also unchanged?
- In general, no!
- For Jupiter, yes! Due to its strong vertical stratification and rapid rotation

Equilibrium in Horizontal

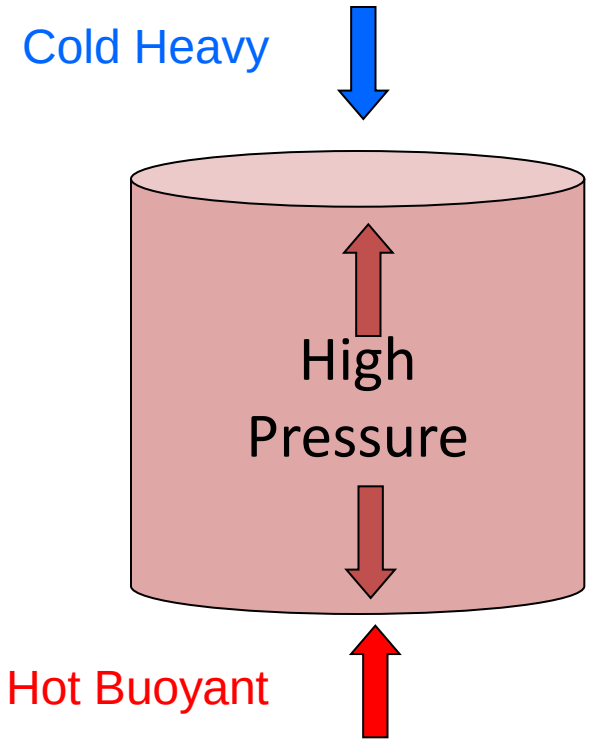
- Horizontal momentum equation:
- For Ro $\leq$ 1, Geostrophic balance between gradient of pressure and the Coriolis force.
- Anticyclones have high pressure centers .



$$\Delta P / L_{\perp} = \rho f v_{\perp}$$

Vertical Forces Within a Vortex

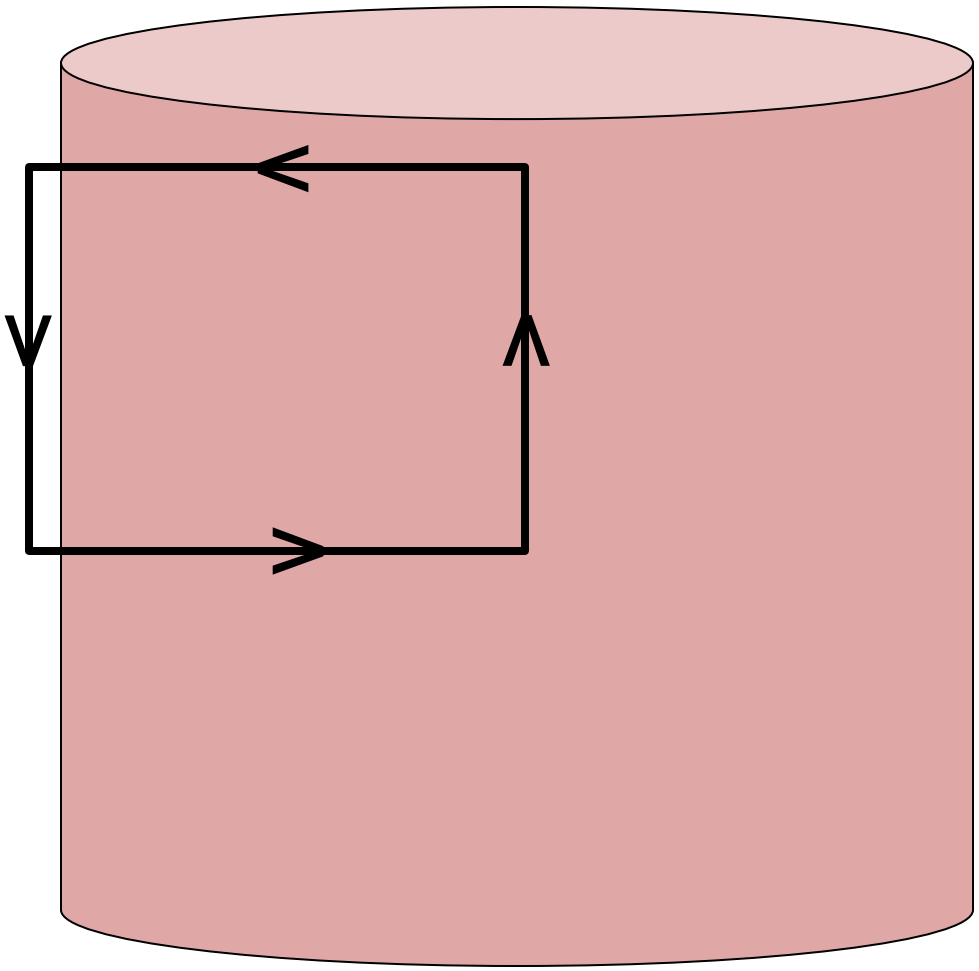
- Hydrostatic balance, High pressure center
- Hot, buoyant bottom, Cold, heavy top



$$g\,\Delta\rho = -\,\Delta P/D$$

- ΔP is known because $L_\perp$ and $v_\perp$ can be measured
- $\Delta\rho$ would be known if D were known
- But then ΔT would be known by ideal gas law: $\Delta P/P = \Delta\rho/\rho + \Delta T/T$
- But then ΔS would be known by second law: $\Delta S/c_p = (c_v/c_p)\,\Delta P/P - \Delta\rho/\rho$
- What is D?

The change in S along a closed path is zero



Closed path is not a streamline

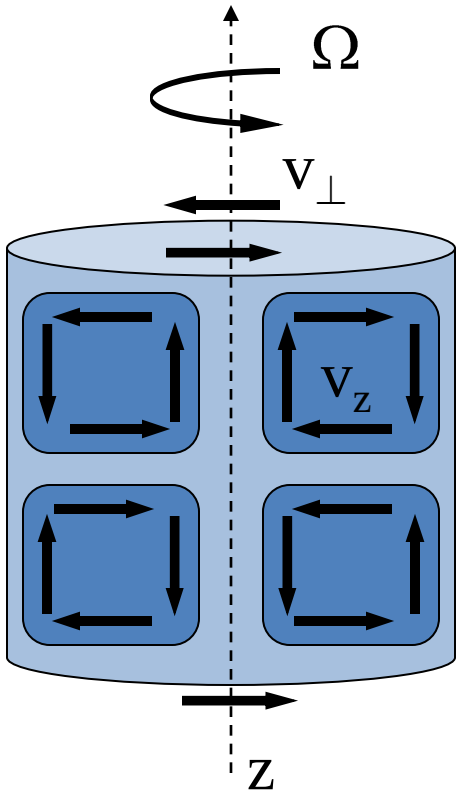
The value of ΔS along the two horizontal legs are know as functions of D

The value of ΔS along the vertical central axis is zero

The value of ΔS along the vertical axis outside the vortex is $D\,(d\langle S\rangle/dz)$

Role of v_z

- In sub-adiabatic flow: rising cools the fluid while sinking warms it.
- This in turn creates cold, heavy top lids and warm, buoyant bottom lids.
- Magnitude of v_z is set by dissipation time and by equipartition of the vertical energy
- Numerical calculations confirm scaling



Is this Ekman Circulation?

- NO
- Most of the vertical flow that rises along the central axis does not escape the vortex, but instead descends back to the mid-plane in an annular ring.
- Very little flow escapes through the top & bottom. That flow does transfer torque between the ambient flow and the flow the vortex. Its velocity is ~10^{-6} v_z.

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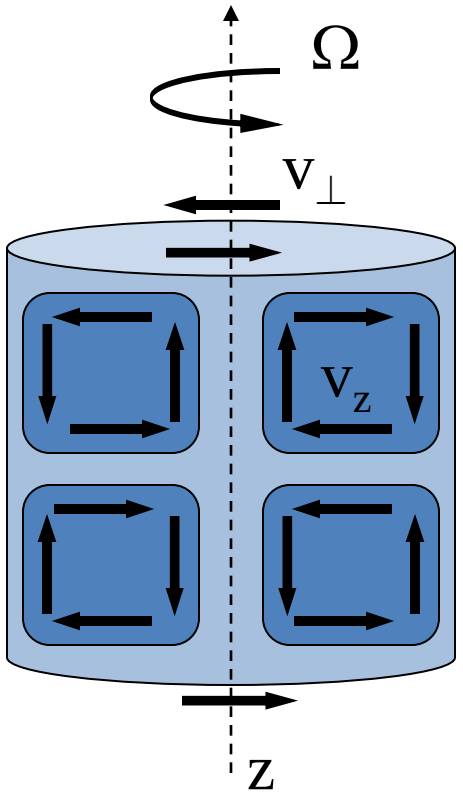
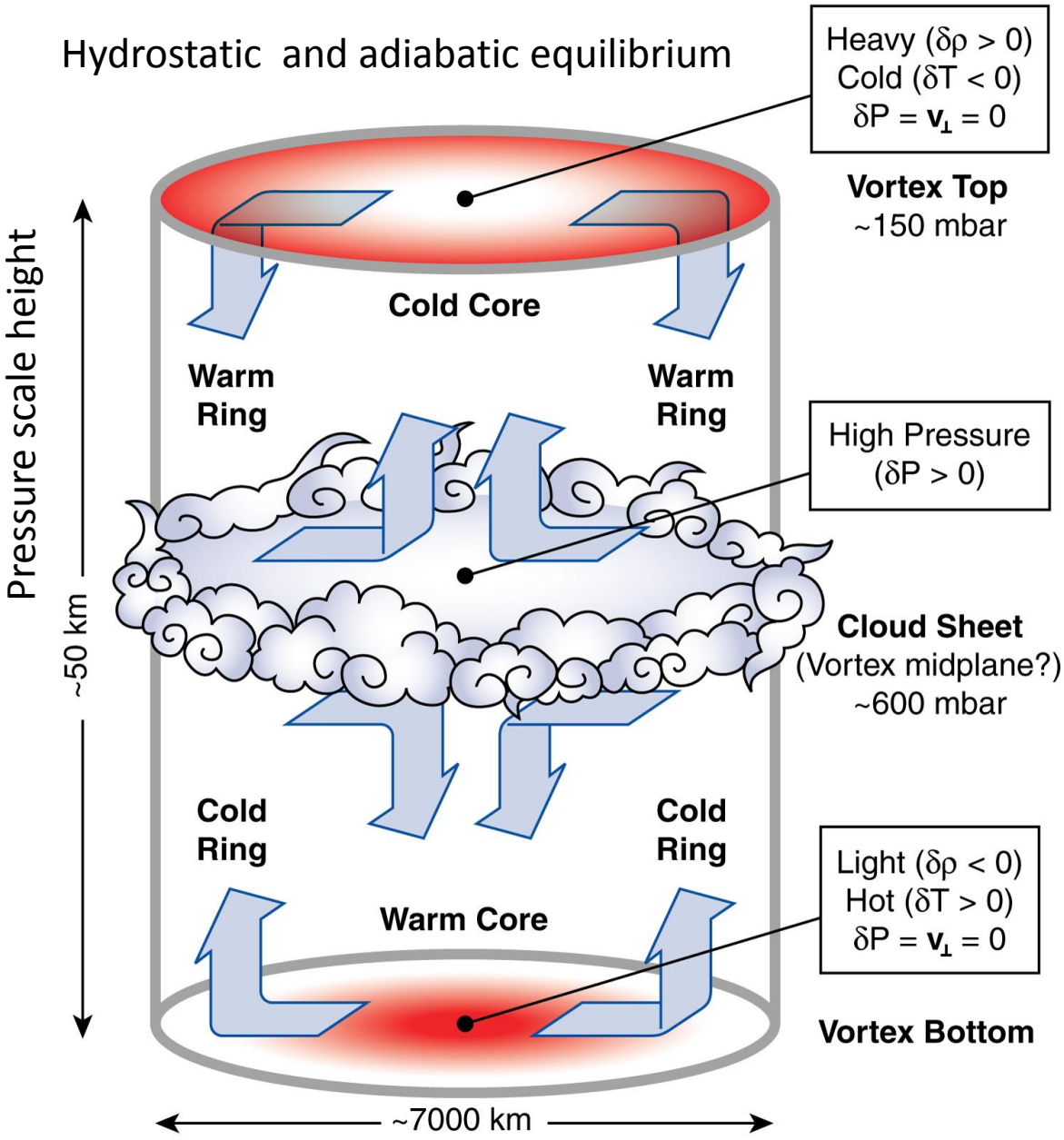
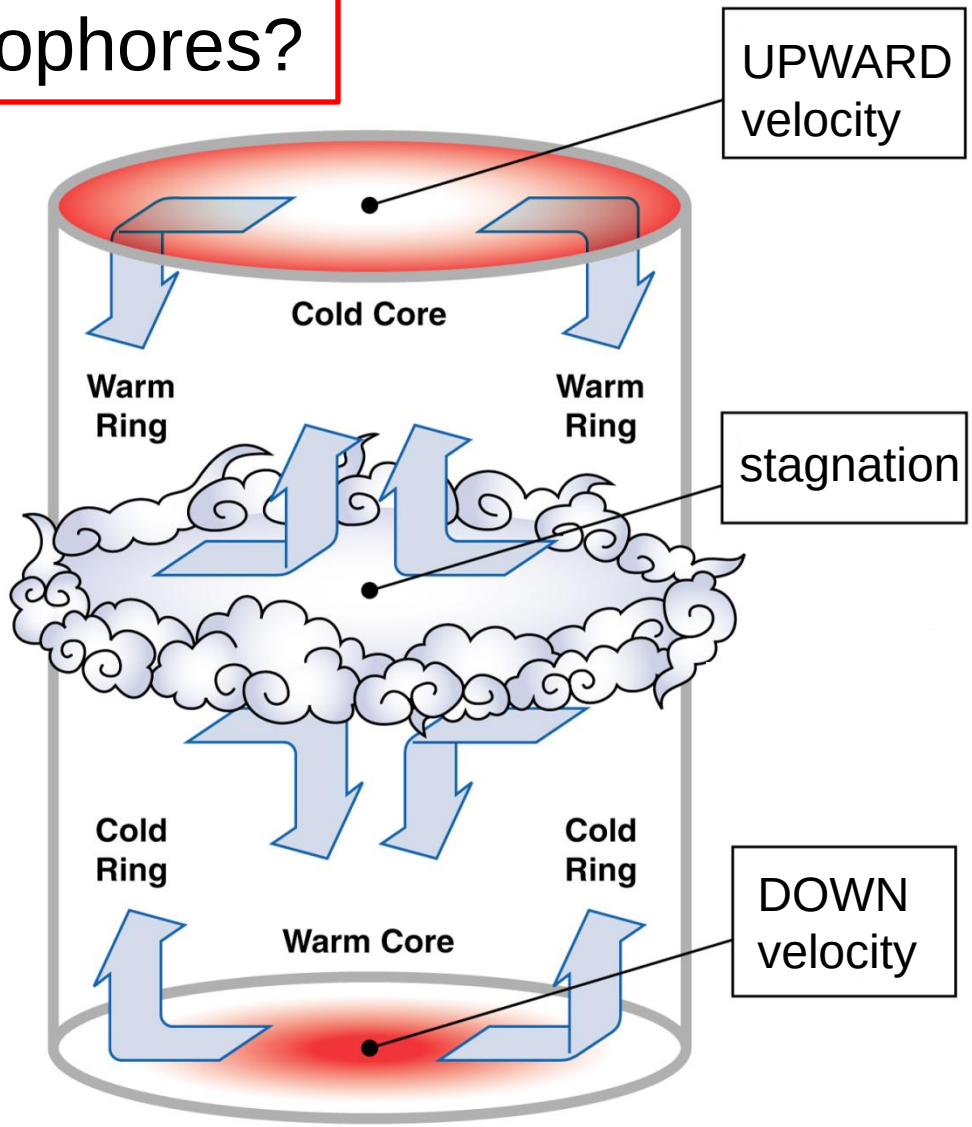



Hydrostatic and adiabatic equilibrium
Heavy (δρ > 0)
Cold (δT < 0)
δP = v⊥ = 0
Vortex Top
~150 mbar
Cold Core
Warm Ring
Warm Ring
High Pressure
(δP > 0)
Cloud Sheet
(Vortex midplane?)
~600 mbar
Cold Ring
Cold Ring
Warm Core
Light (δρ < 0)
Hot (δT > 0)
δP = v⊥ = 0
Vortex Bottom
Pressure scale height
~50 km
~7000 km

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?



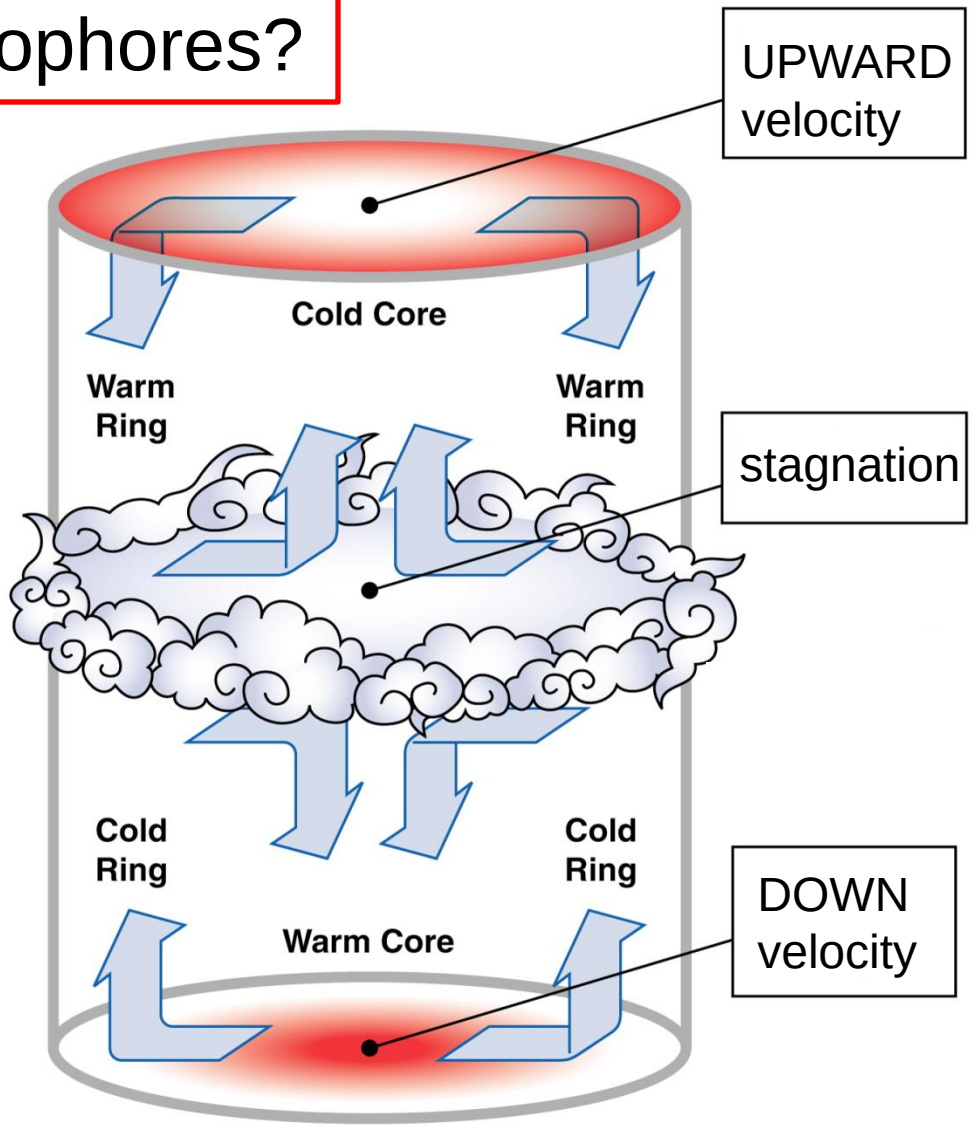
Cloud Layer is Like a Cloud Chamber Bob West

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



Conclusions

- 2D velocity, dimensions, relative thermal properties unchanged
- Quasi-linearity $\Longrightarrow$ 3D also unchanged
- Dredging $\not\Longrightarrow$ red
- Direct temp. measurements are difficult: deconvolve temp., abundance, pressure, etc.
- Global temperature explains ring, its history and GRS if temp. $\Longrightarrow$ red chromophore chem.