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The Critical Latitudes of Jupiter and Saturn

From Major Liabilities to Major Assets

Timothy E. Dowling, *University of Louisville*

Critical Latitude:
Local max. or min.
of PV = spin/depth ratio

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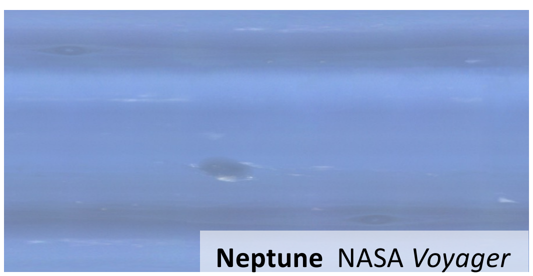
Critical Latitude:
Where Rossby waves reverse direction

(The ice giants are not in this discussion because they do not have multiple critical latitudes.)



Neptune NASA *Voyager*

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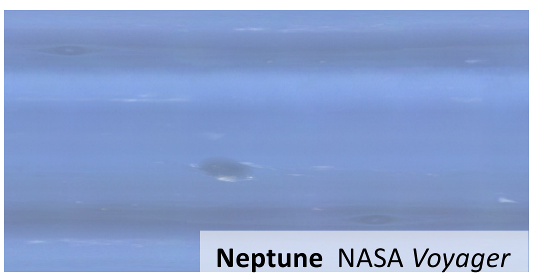
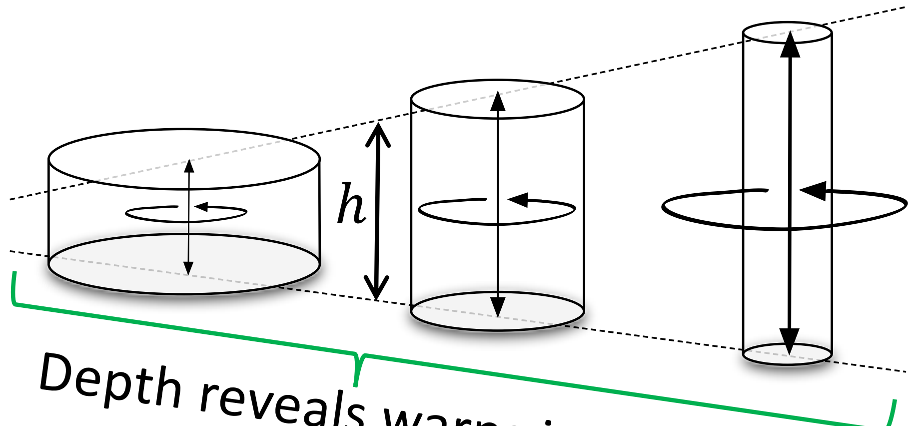


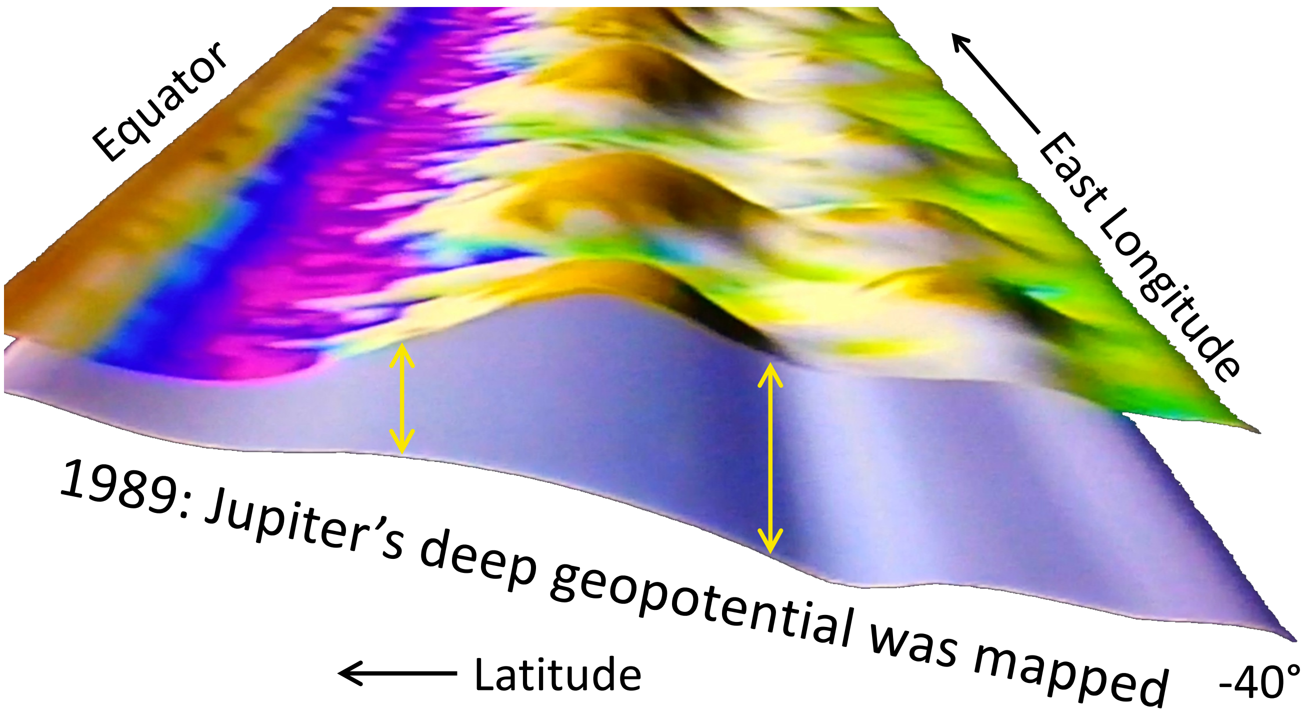
Neptune NASA *Voyager*

Spin is proportional to depth:

$$(\zeta + f) = PV * h$$



Depth reveals warps in the underlying geopotential



Deep undulations are the tops of deep jets.

✓*Juno*

1988: Jupiter's Great Red Spot (GRS) was discovered to be twice as deep on its poleward side as its equatorward side.

Juno: PJ7 MWR, Cheng Li (private comm.)

References

Dowling and Ingersoll, 1988, *J. Atmos. Sci.* 45, 1380–1396

Dowling and Ingersoll, 1989, *J. Atmos. Sci.* 46, 3256–3278

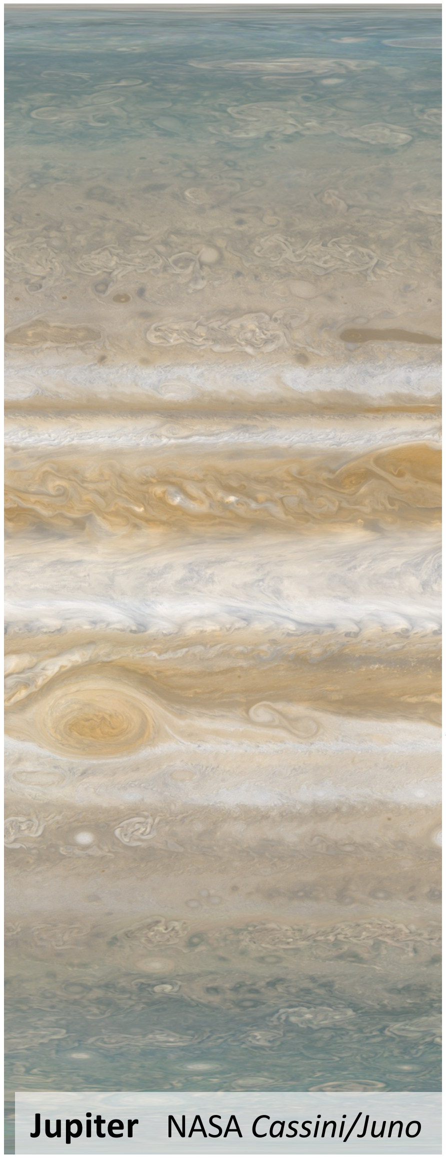
Kaspi et al., 2018, *Nature 555*, 223–226

The tops of Jupiter's deep jets were discovered by:

1. Abandoning the established approach of assuming one form of interior-jet structure or another.

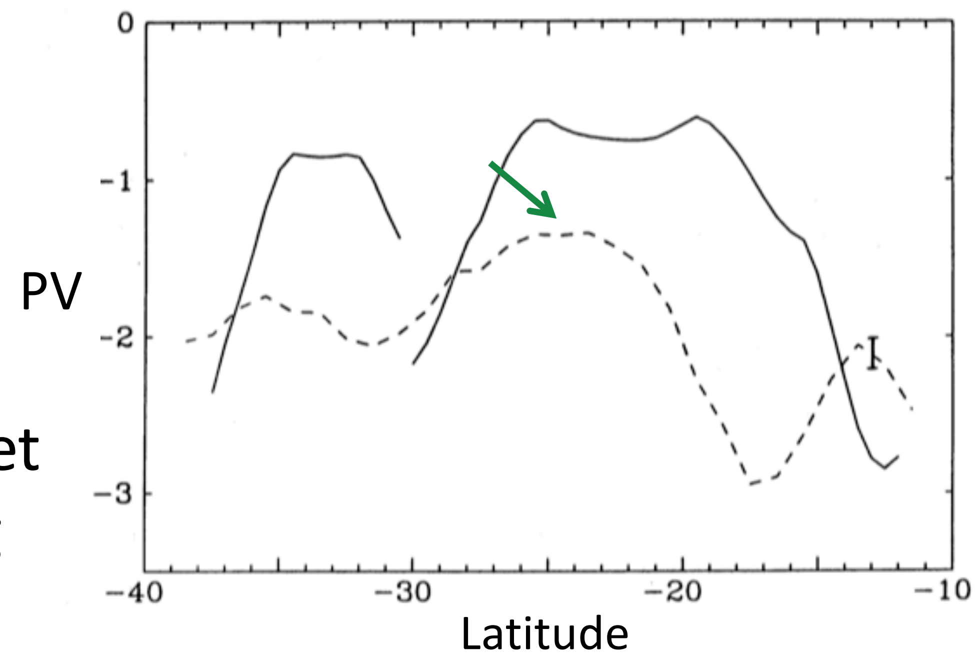
Instead, by:

2. *Inferring* interior jets from *Voyager* vorticity (spin) data.



1989:
The GRS straddles a critical latitude.

Juno has been quiet to date regarding critical latitudes.



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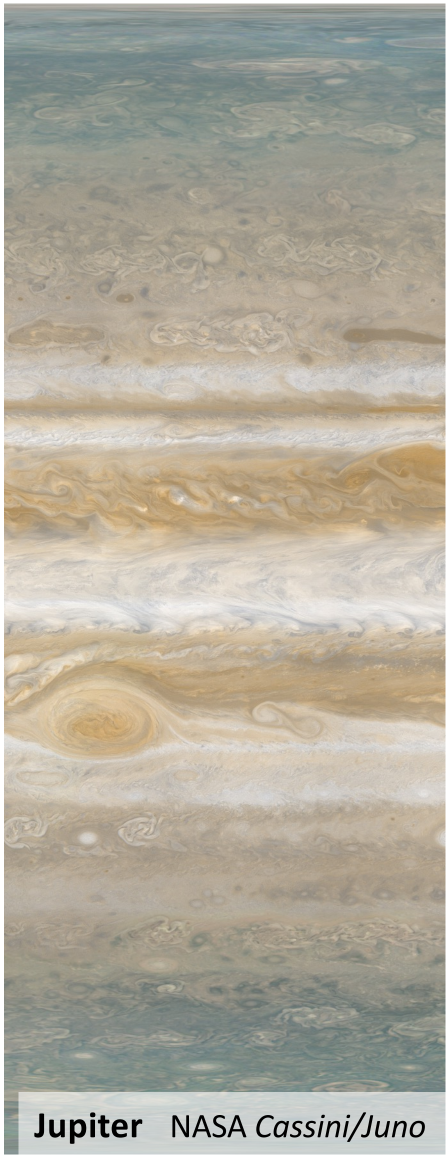
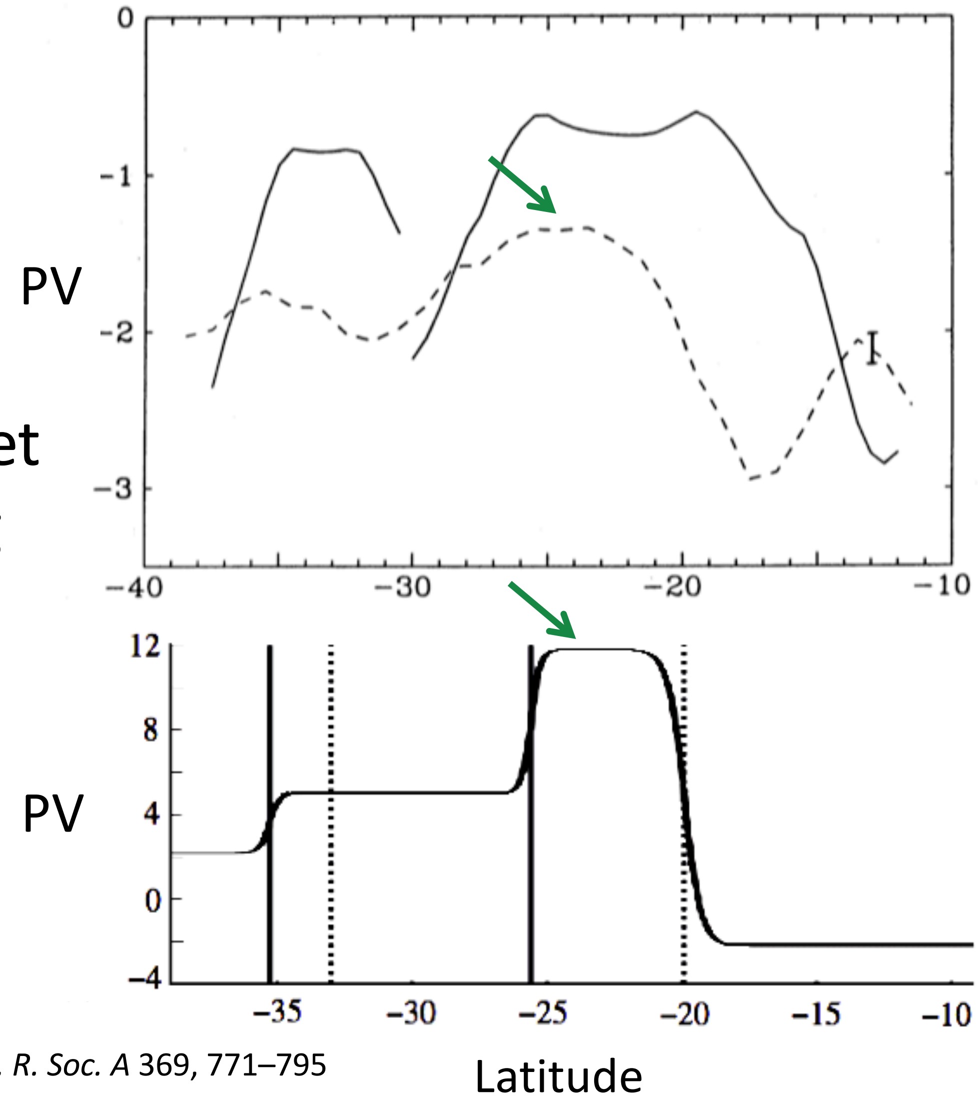
✓*2011:*
Marcus & Shetty





Marcus and Shetty, 2011, *Phi. Trans. R. Soc. A* 369, 771–795

Jet Stream Theorems

	Unstable Jet	Stable Jet
Necessary Condition	Critical latitude	
Sufficient Condition		No critical latitude

This makes it appear that critical latitudes are major liabilities.

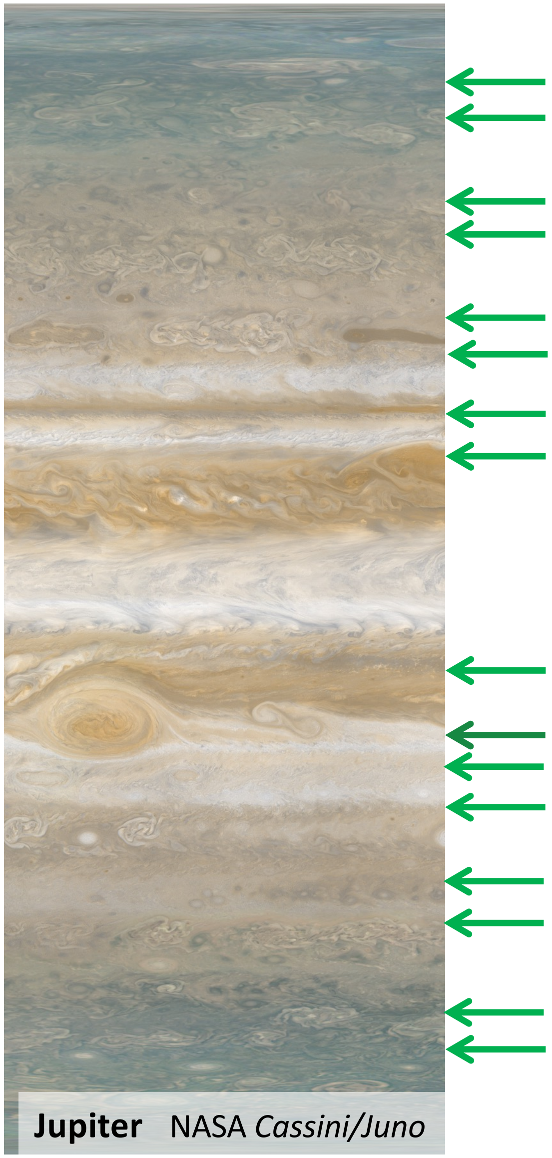
But this is a common mistake. For example:

In the *Wizard of Oz*, Dorothy thinks “witches are old and ugly”…

but then she learns that “only <u>bad</u> witches are ugly.”

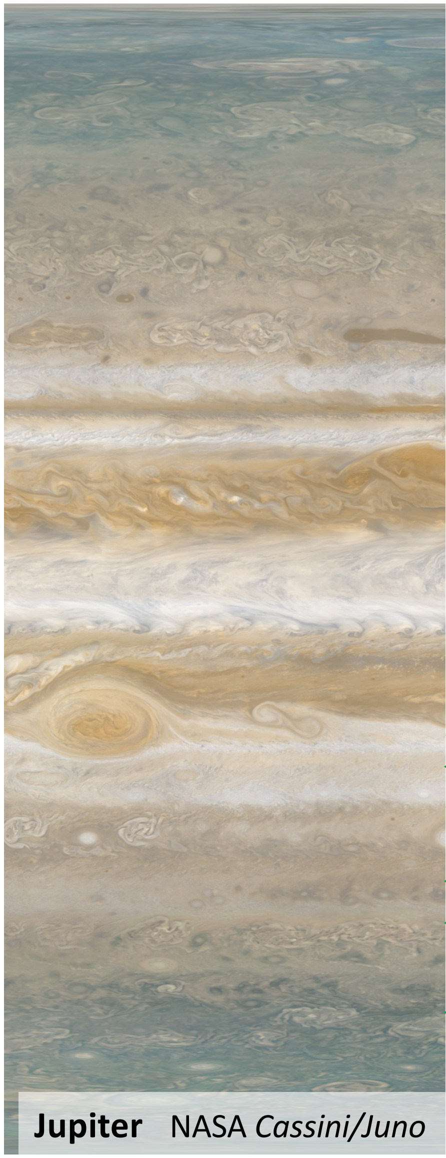
Just so, we need to fill in the blank:

Only ___?___ critical latitudes are unstable.



2006: Wind and temperature data from *Voyager* and *Cassini* revealed that Jupiter is striped with critical latitudes (Read et al.).

Read et al., 2006, *Q. J. R. Meteorol. Soc.* 132, 1577–1603



Jupiter NASA *Cassini/Juno*

2006: Wind and temperature data from *Voyager* and *Cassini* revealed that Jupiter is striped with critical latitudes (Read et al.).

Read et al., 2006, *Q. J. R. Meteorol. Soc.* 132, 1577–1603

2009: Wind and temperature data from *Voyager* and *Cassini* revealed that Saturn is striped with critical latitudes (Read et al.).

Read et al., 2009, *Planet. Space Sci.* 57, 1682–1698

There is not
one ~~elephant~~ witch
in the room.

Saturn NASA *Cassini* (Jónsson)

1995: Multiple critical latitudes shown to maintain stability by phase locking the fastest (longest) Rossby waves.

Dowling, 1995, *Ann. Rev. Fluid Mech.* 27, 293–334

2009: The longest Rossby waves lock onto the planet's rotation period, yielding:

Read, Dowling & Schubert, 2009, *Nature* 460, 608–610

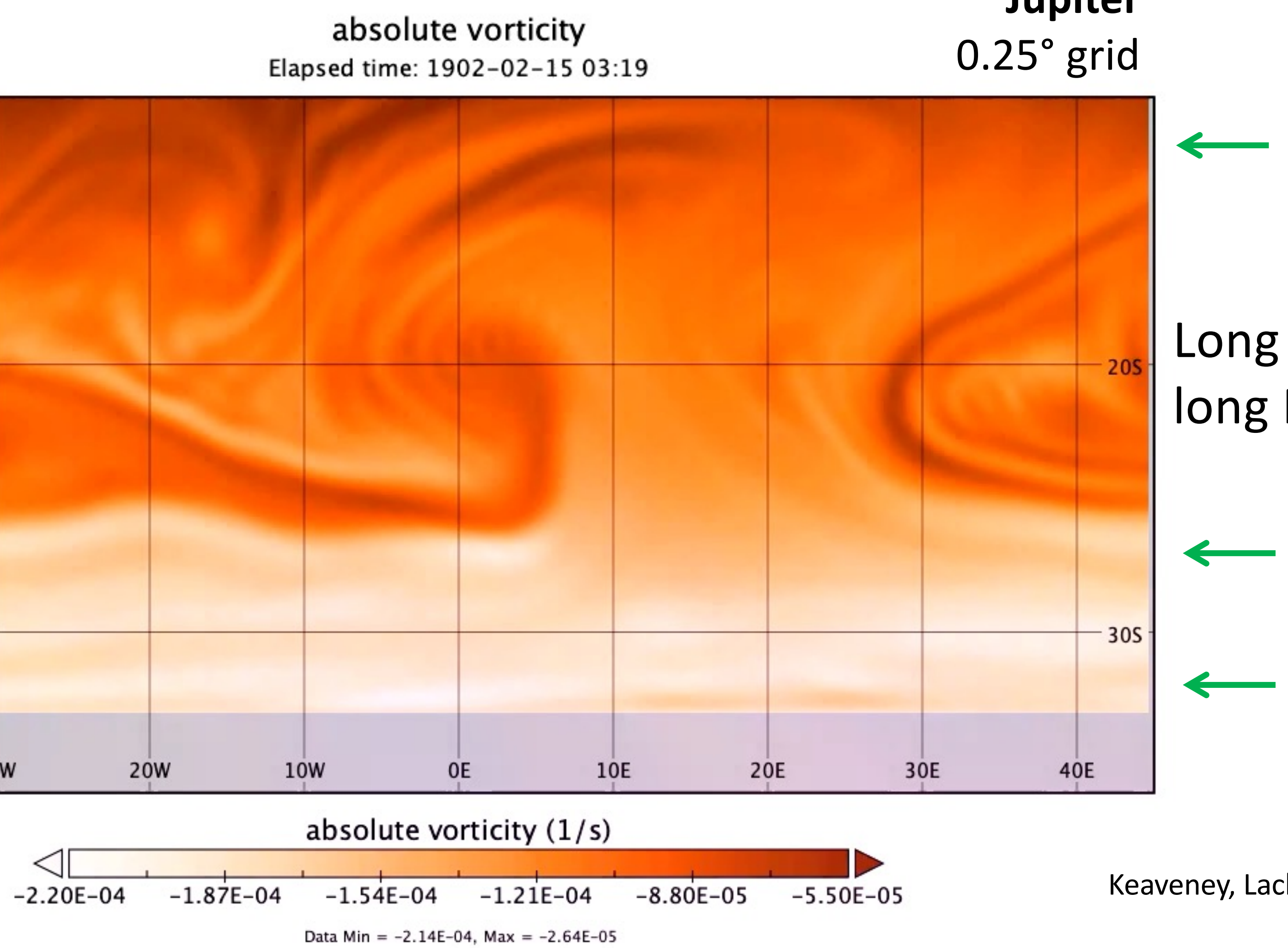
Jupiter: $9^h\ 55^m$ Saturn: $10^h\ 34^m$

Multiple critical latitudes are major assets.

To use these assets, we need to understand how Rossby waves and critical latitudes govern jet stability.

Rossby Wave Example

EPIC 5.22
Jupiter
0.25° grid



Long undulations are long Rossby waves

Keaveney, Lackmann & Dowling

1880: Shear stability theorems began appearing.

Rayleigh (1880)
Kuo (1949)
Fjørtoft (1950)
Charney & Stern (1962)
Arnol'd (1966)
Ripa (1983)

2014: Shear stability theorems were non-dimensionalized for the first time.

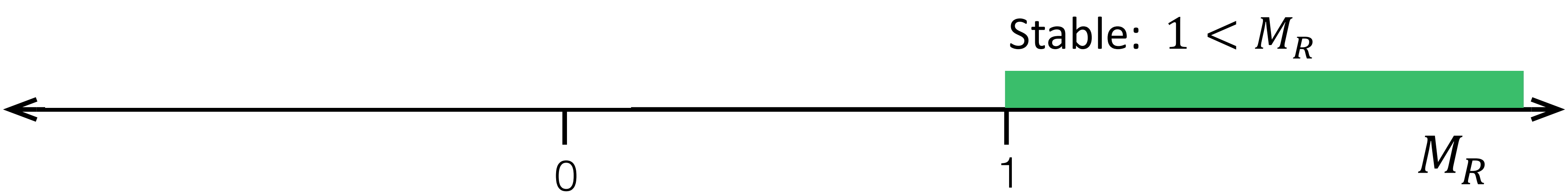
Dowling, 2014, Int. J. Modern Phys. D 23, 1430006

“Supersonic” critical latitudes are stable.

$\boxed{\text{“Supersonic” critical latitudes are stable.}}$

The key to understanding how
critical latitudes control Rossby waves is
the non-dimensional Rossby Mach number, M_{R} .

Rossby waves are unidirectional,
hence there are 2 “supersonic” cases:



2014: The reciprocal Rossby Mach number
concatenates these into a single stability region.

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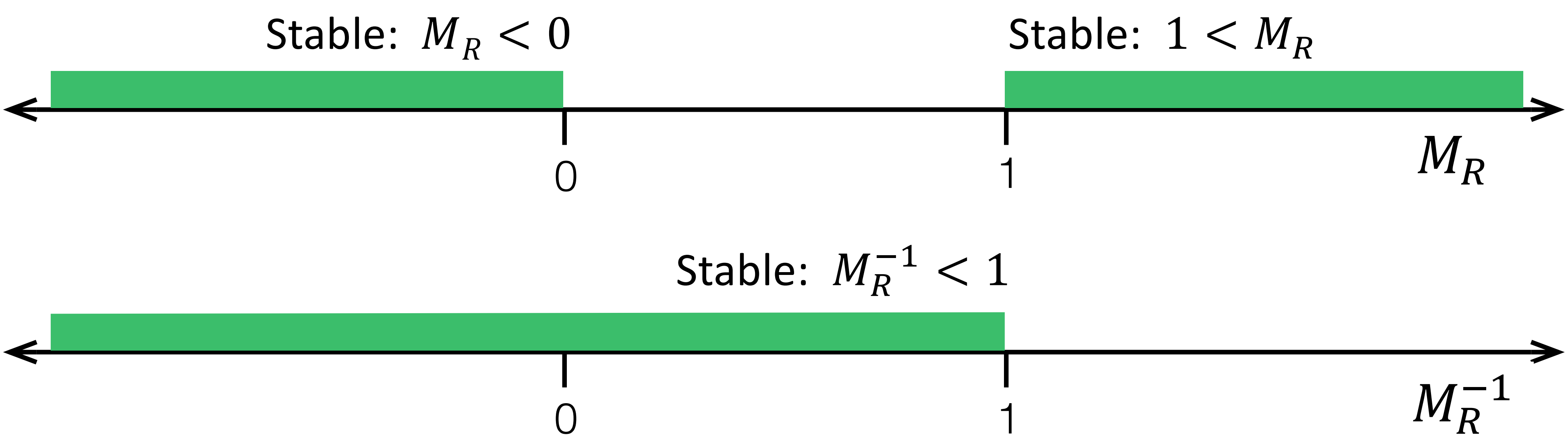
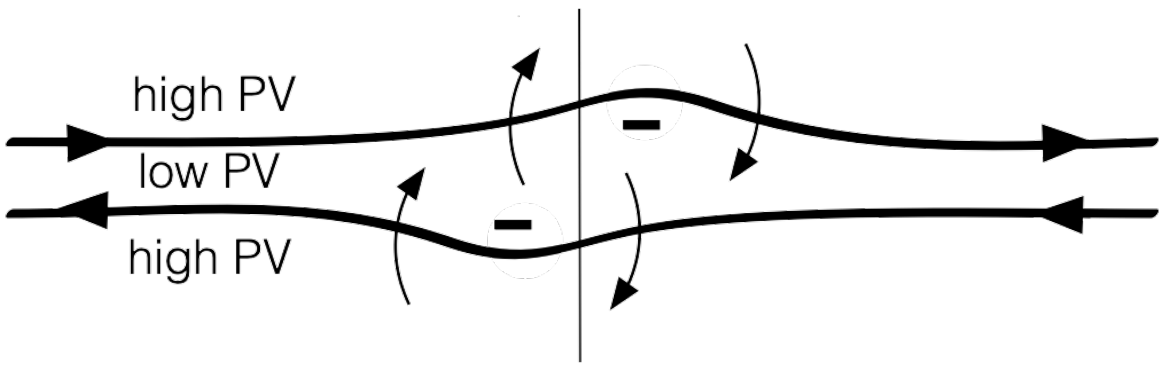


2014: The reciprocal Rossby Mach number concatenates these into a single stability region.

How “supersonic” critical latitudes work, $M_R^{-1} < 1$



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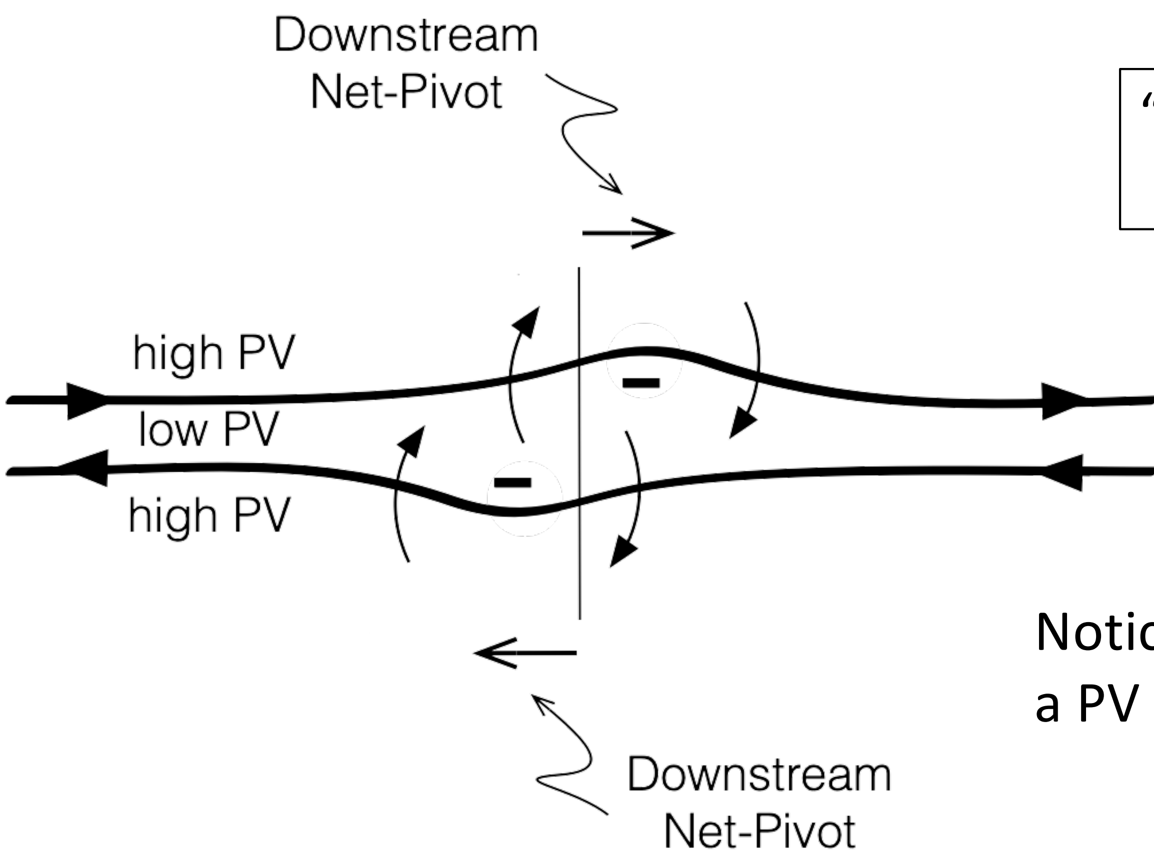
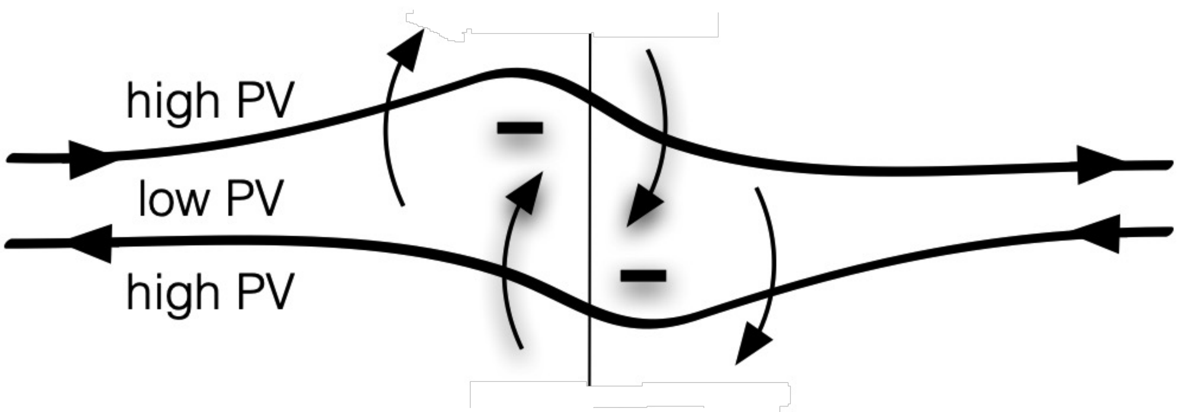


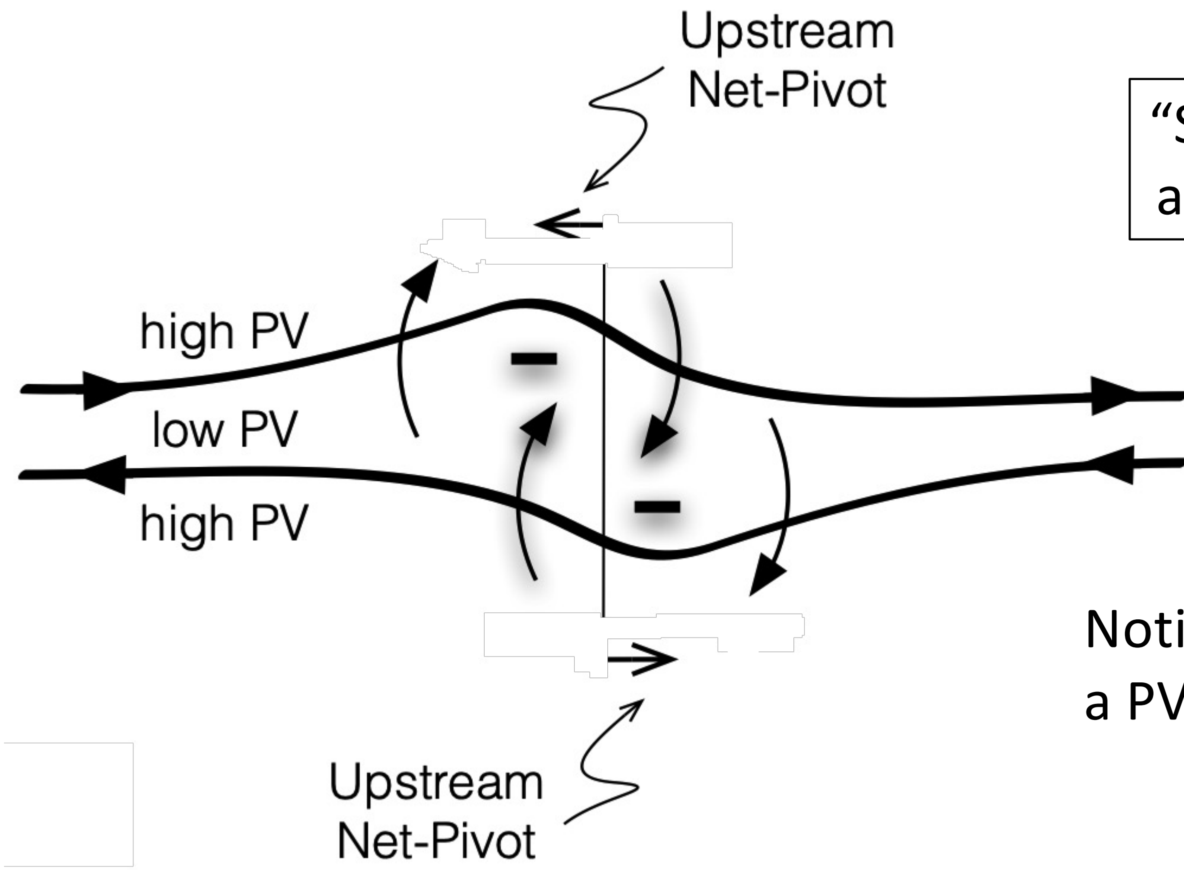
“Supersonic” critical latitudes are proven to be stable.

Notice the negative feedback when a PV eddy pivots with the shear.

How “subsonic” critical latitudes work, $M_R^{-1} > 1$



How “subsonic” critical latitudes work, $M_R^{-1} > 1$



“Subsonic” critical latitudes are fraught with instability.

Notice the positive feedback when a PV eddy pivots against the shear.

Jet Stream Theorems, Updated

	Unstable Jet	Stable Jet
Necessary Condition	Critical latitude	
Sufficient Condition		No critical latitude

Jet Stream Theorems, Updated

	Unstable Jet	Stable Jet
Necessary Condition	"Subsonic" critical latitude, $M_R^{-1} > 1$	
Sufficient Condition		No "subsonic" critical latitude

This makes it appear that "subsonic" critical latitudes are unstable.

Jet Stream Theorems, Sharp

To prove that a “subsonic” critical latitude
is both necessary and sufficient for shear instability:

1. Prove that a “subsonic” critical latitude is necessary and sufficient for the existence of a neutral mode.

2. Prove that a neutral mode is necessary and sufficient for the existence of an unstable mode.

Jet Stream Theorems, Sharp

	Unstable Jet	Stable Jet
Necessary Condition / Sufficient Condition	"Subsonic" critical latitude, $M_R^{-1} > 1$	No "subsonic" critical latitude

Deguchi, Hirota, and Dowling, Stability of alternating jets: necessary and sufficient conditions

To Do List

- Determine winds and temperatures from PV inversion (elliptic operator) as in Sun and Lindzen (1994), but with $M_R^{-1} = 1$ instead of $M_R^{-1} = 0$ (w/ *Voyager* vorticity paradigm shift).
- Add the shear stability constraint, $M_R^{-1} \leq 1$, to *Juno* gravity inversions everywhere there are jets (troposphere and interior).
- For systems with multiple stable critical latitudes (Jupiter, Saturn), apply the tight constraint (major asset), $M_R^{-1} \cong 1$:

  1989: tops of Jupiter's deep jets (w/o *Juno* gravity data)

  2009: Saturn's 10^h34^m period (w/o *Cassini* ring-wave data)