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December 27, 2023

# **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

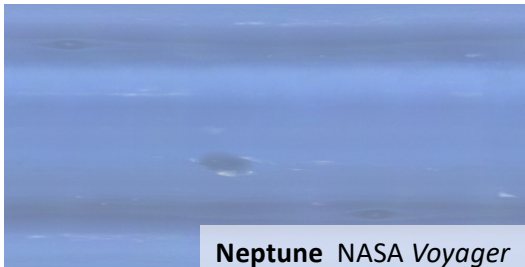
# The Critical Latitudes of Jupiter and Saturn

## *From Major Liabilities to Major Assets*

Timothy E. Dowling, *University of Louisville*

*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

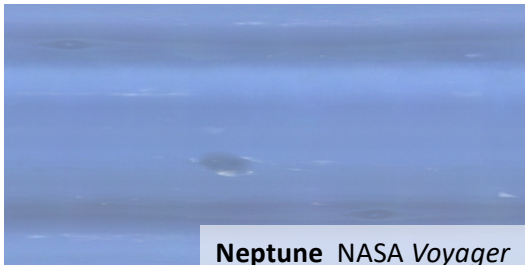
# The Critical Latitudes of Jupiter and Saturn

## *From Major Liabilities to Major Assets*

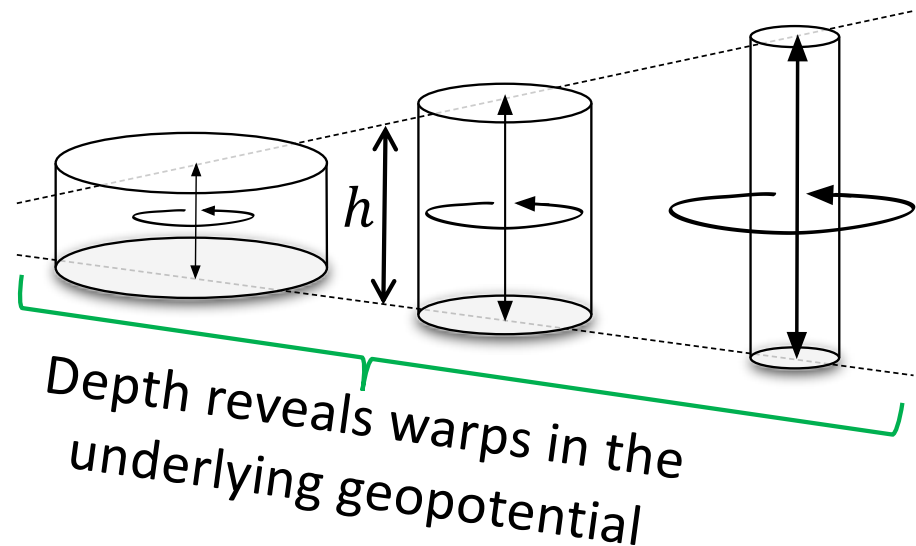
Timothy E. Dowling, *University of Louisville*

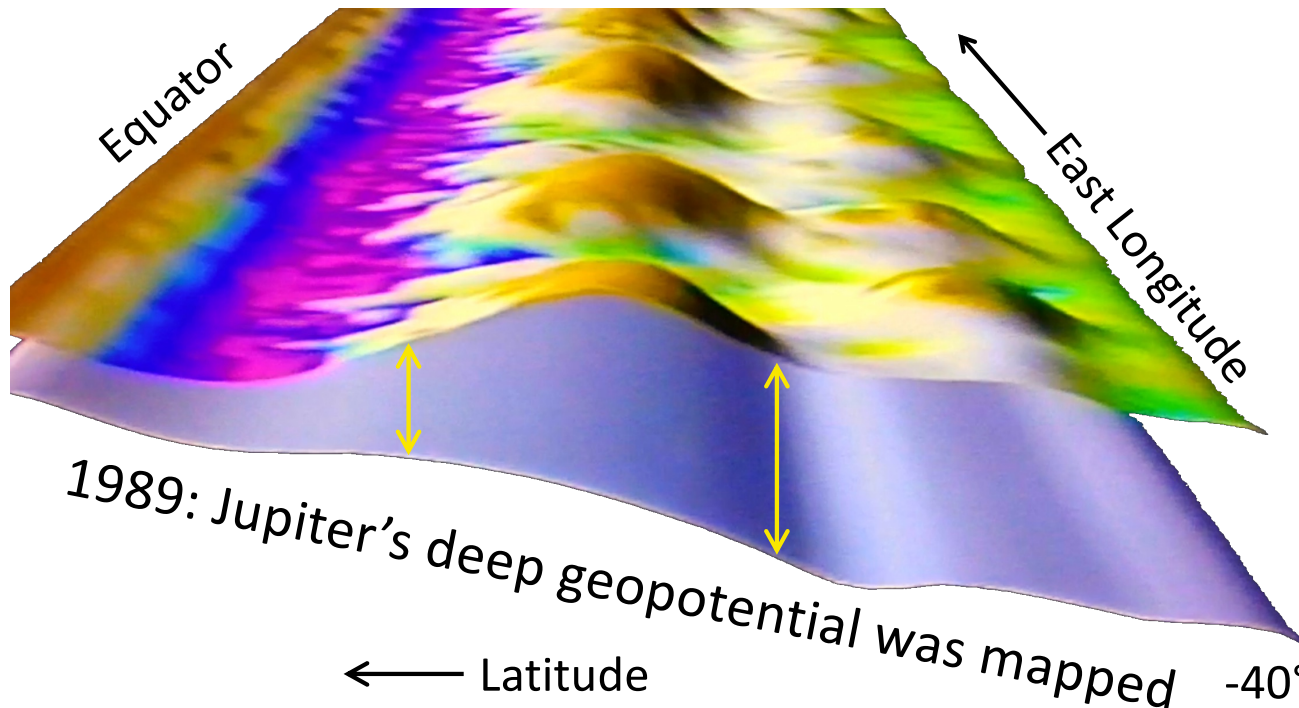
*Critical Latitude:*  
Where Rossby waves  
reverse direction

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*Spin is proportional to depth:*  
 $(\zeta + f) = PV * h$





*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

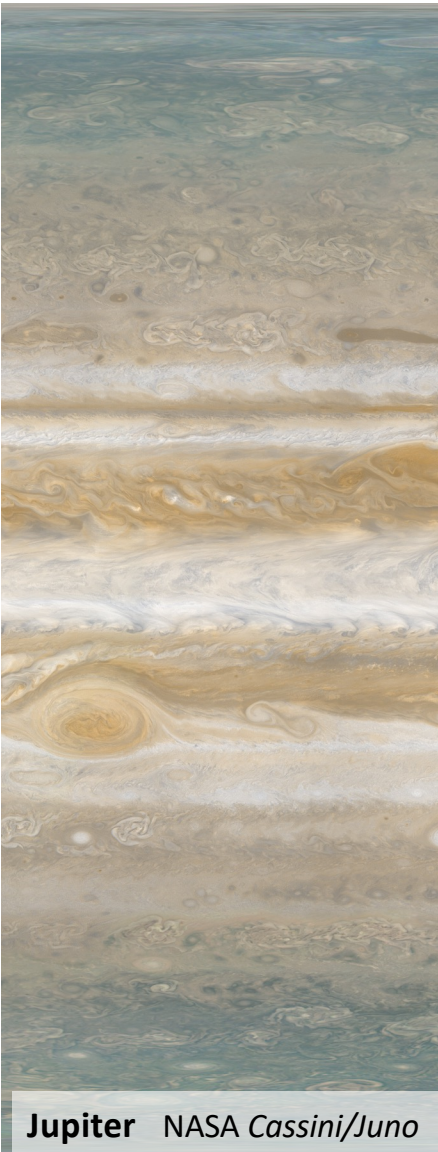
- Dowling and Ingersoll, 1988, *J. Atmos. Sci.* 45, 1380–1396
- Dowling and Ingersoll, 1989, *J. Atmos. Sci.* 46, 3256–3278
- Kaspi et al., 2018, *Nature* 555, 223–226

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.

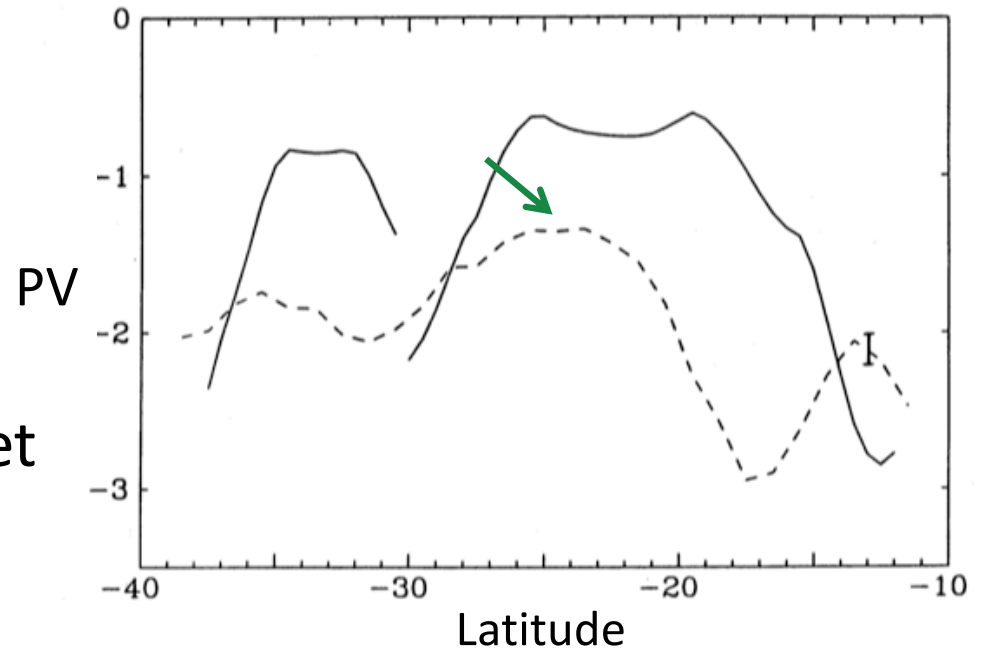
Instead, by:

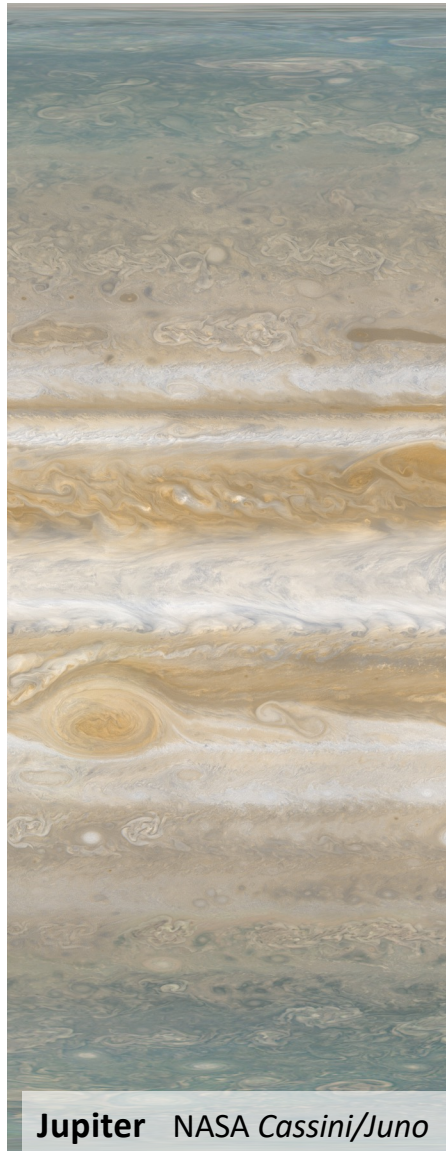
2. *Inferring* interior jets from *Voyager* vorticity (spin) data.



1989:  
The GRS straddles  
a critical latitude.

*Juno* has been quiet  
to date regarding  
critical latitudes.



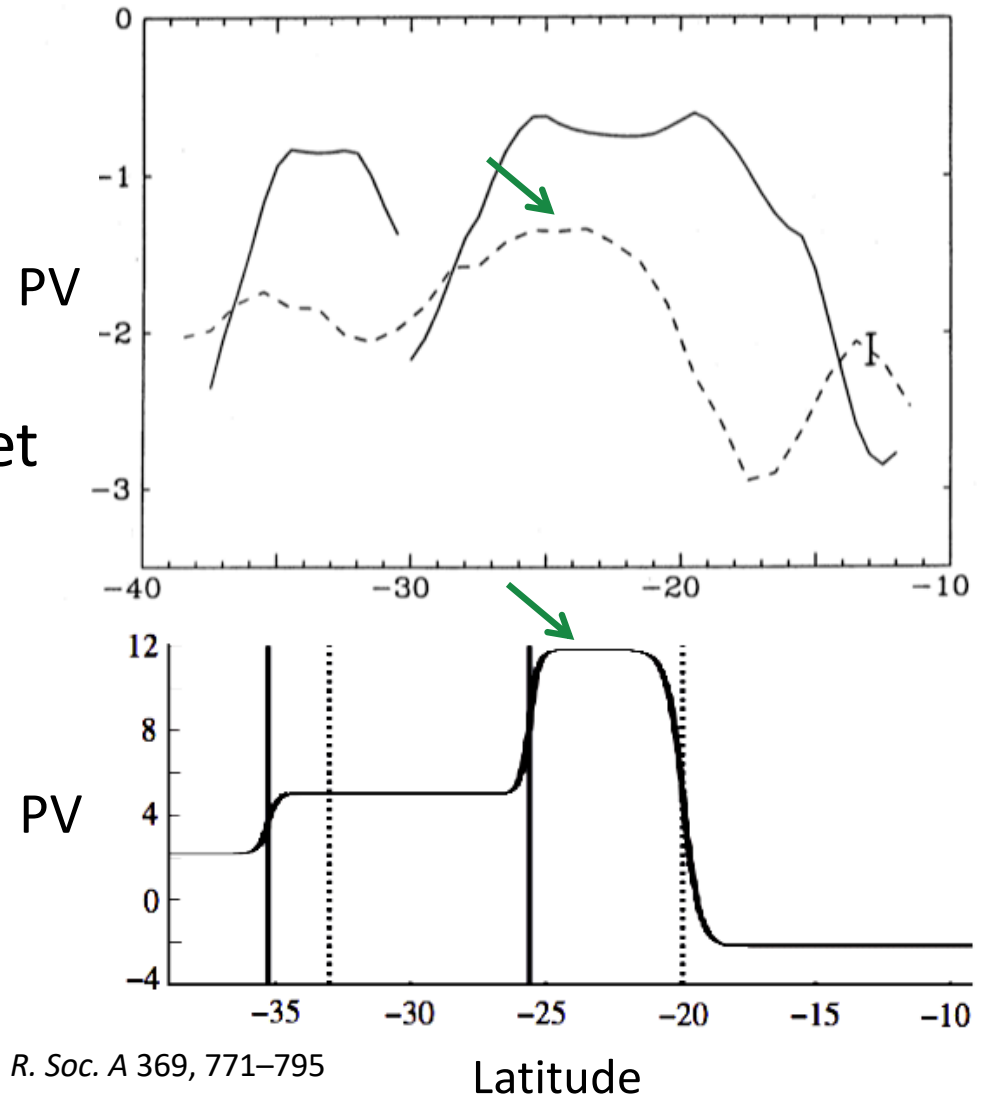


1989:  
The GRS straddles  
a critical latitude.

*Juno* has been quiet  
to date regarding  
critical latitudes.

✓ 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

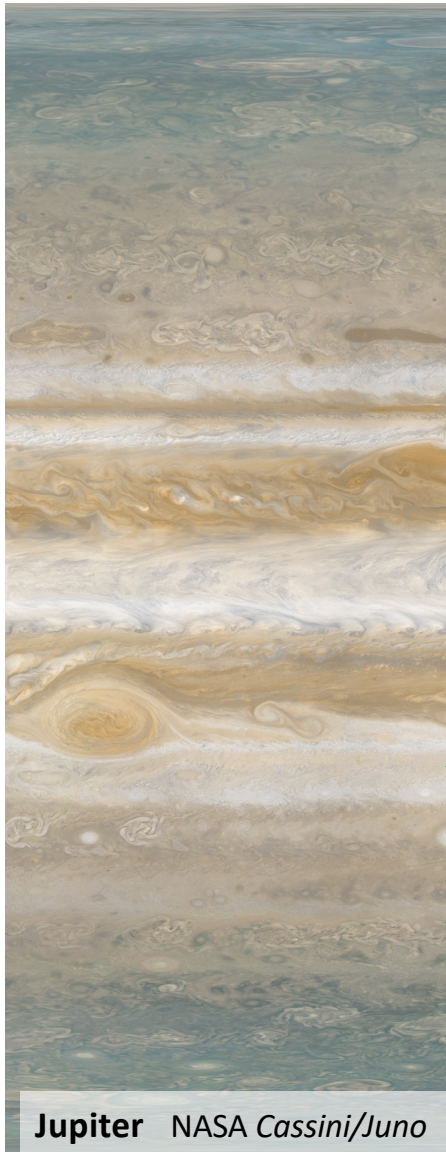
This makes it appear that critical latitudes are major liabilities.

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 bad witches are ugly.”

Just so, we need to fill in the blank:

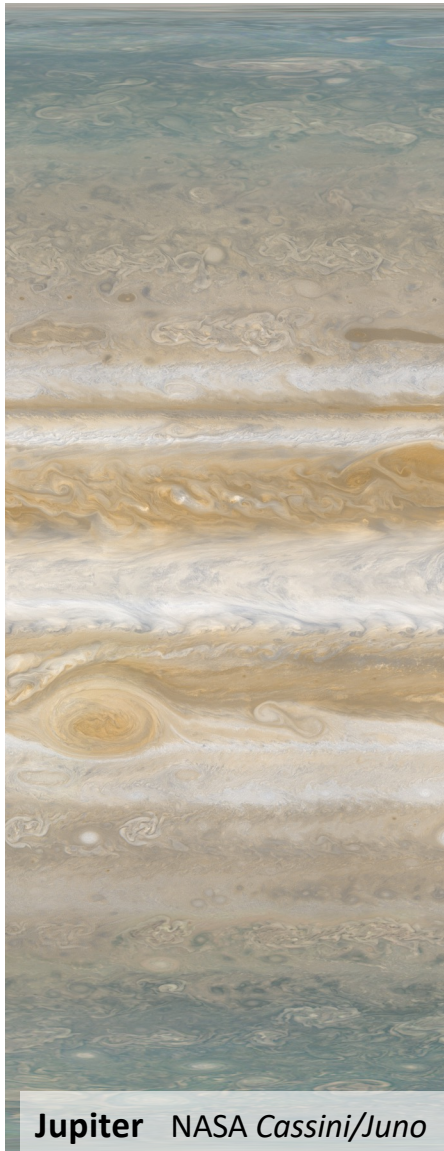
Only \_\_\_\_?\_\_\_\_ critical latitudes are unstable.



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



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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<sup>h</sup> 55<sup>m</sup>      Saturn: 10<sup>h</sup> 34<sup>m</sup>

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

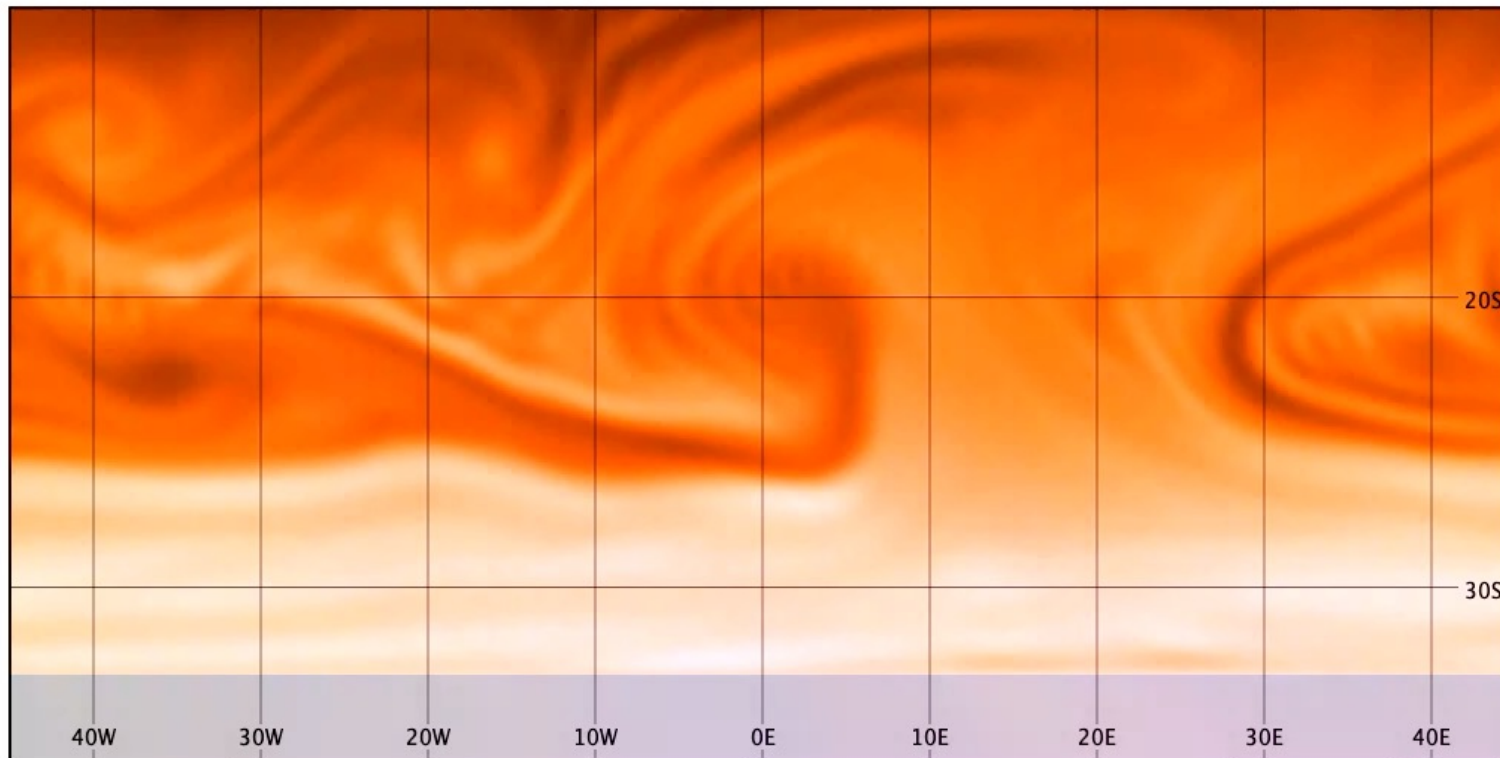
EPIC 5.22

**Jupiter**

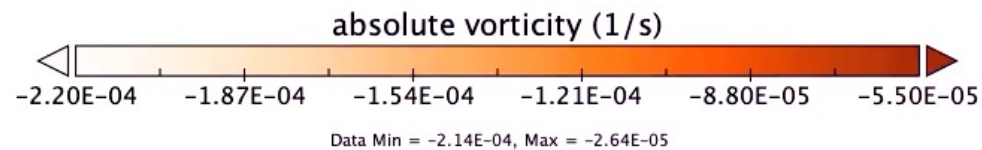
0.25° grid

absolute vorticity

Elapsed time: 1902-02-15 03:19



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

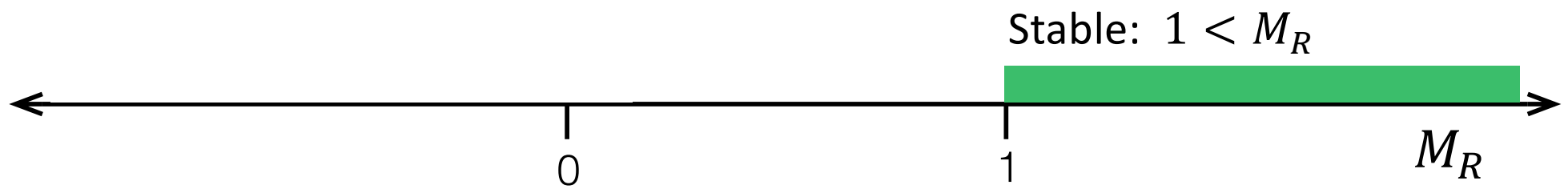
“Supersonic” critical latitudes are stable.

“Supersonic” critical latitudes are stable.

The key to understanding how critical latitudes control Rossby waves is the non-dimensional Rossby Mach number,  $M_R$ .

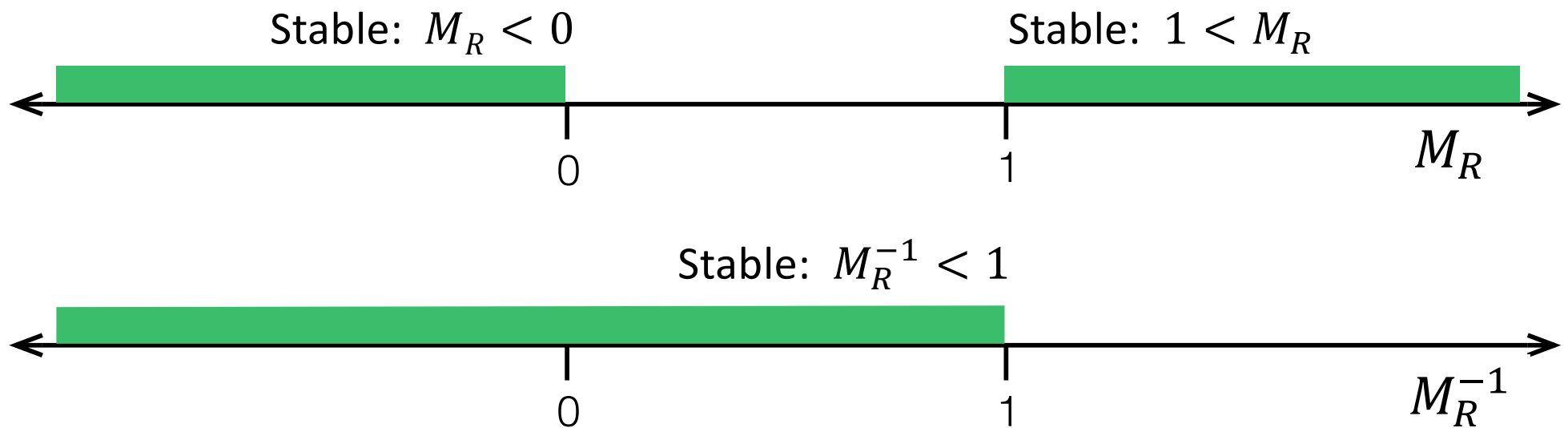


Rossby waves are unidirectional,  
hence there are 2 “supersonic” cases:



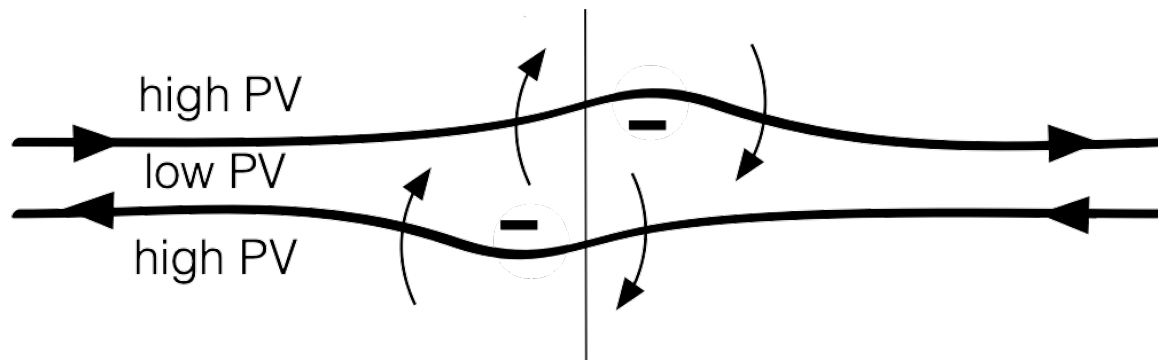
2014: The reciprocal Rossby Mach number  
concatenates these into a single stability region.

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

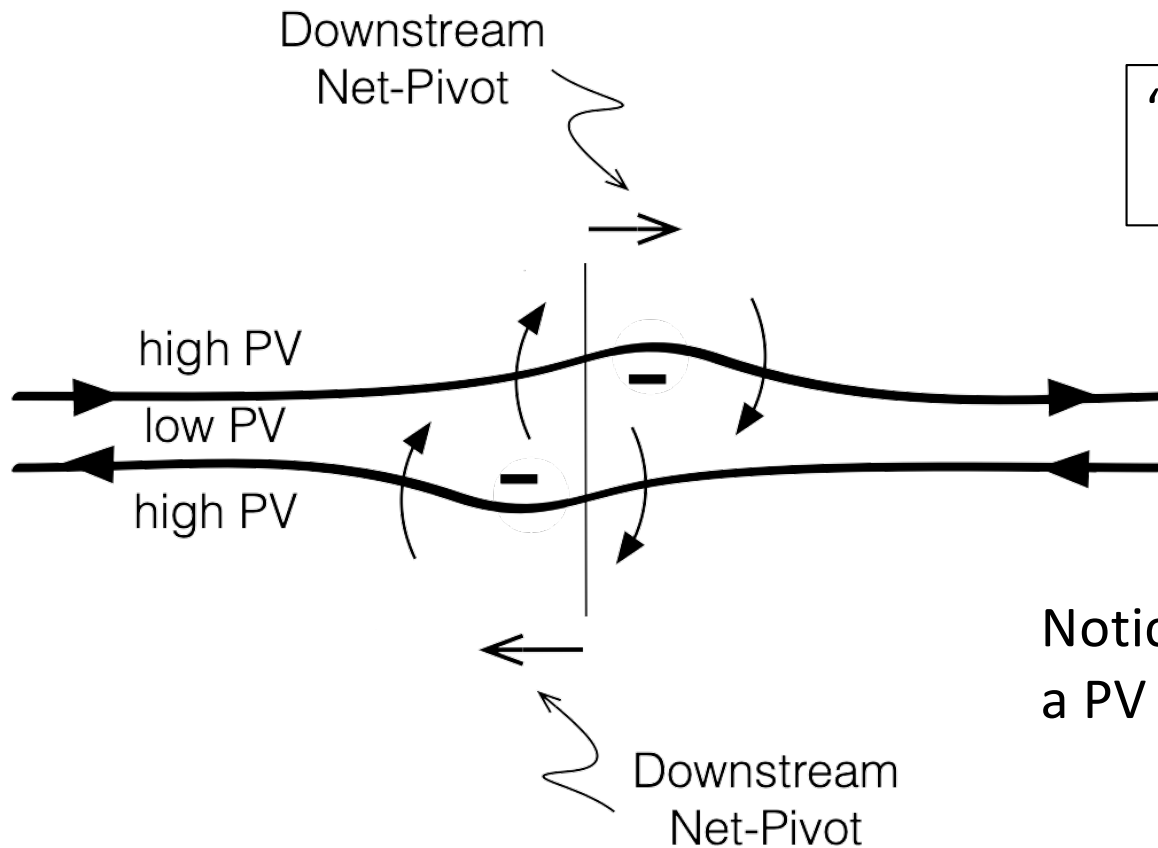


2014: The reciprocal Rossby Mach number  
concatenates these into a single stability region.

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



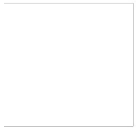
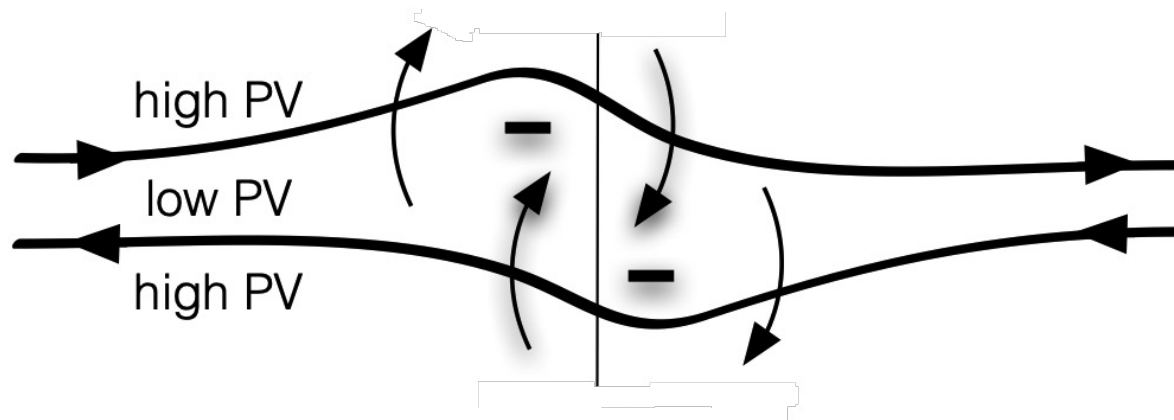
# How “supersonic” critical latitudes work, $M_R^{-1} < 1$



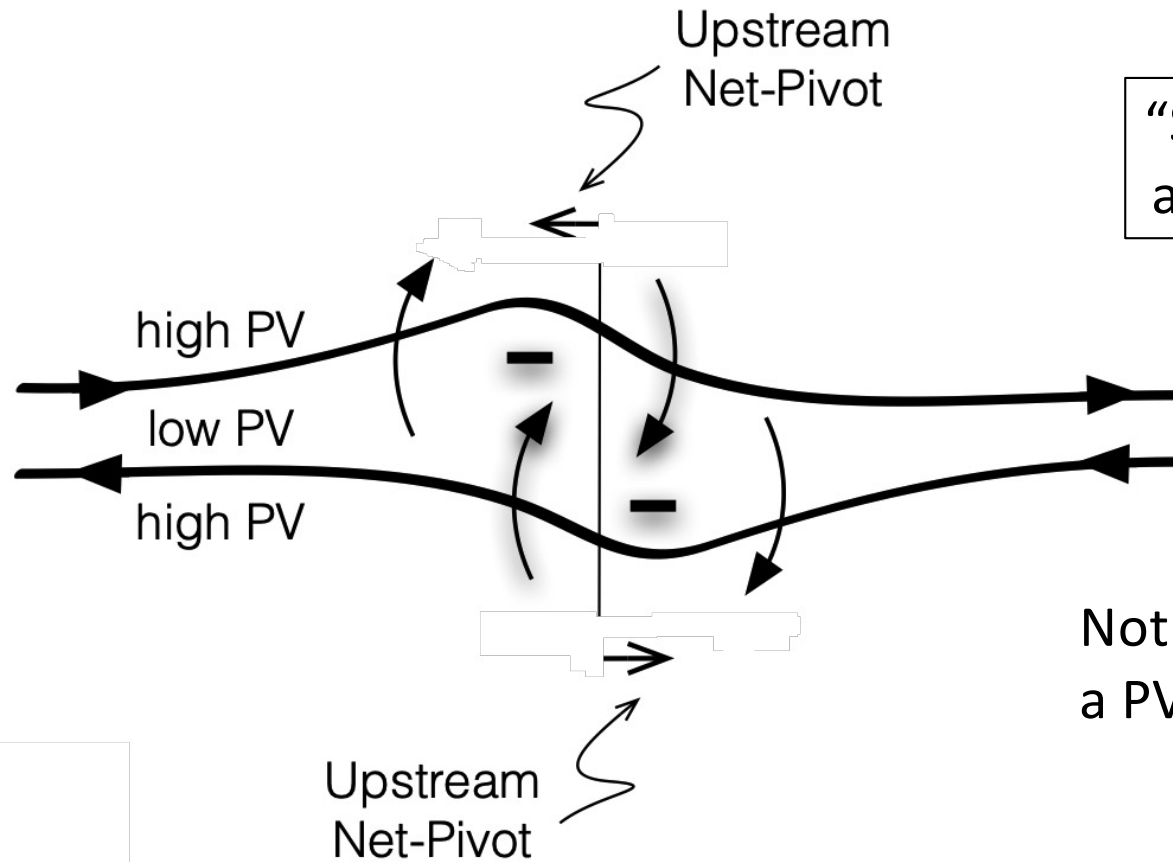
“Supersonic” critical latitudes are proven to be stable.

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	<u>“Subsonic”</u> critical latitude, $M_R^{-1} > 1$	No <u>“subsonic”</u> critical latitude
Sufficient Condition		

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<sup>h</sup>34<sup>m</sup> period (w/o *Cassini* ring-wave data)