WINDS ON VENUS FROM CLOUD TRACKING

And other planets

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What am I doing here?

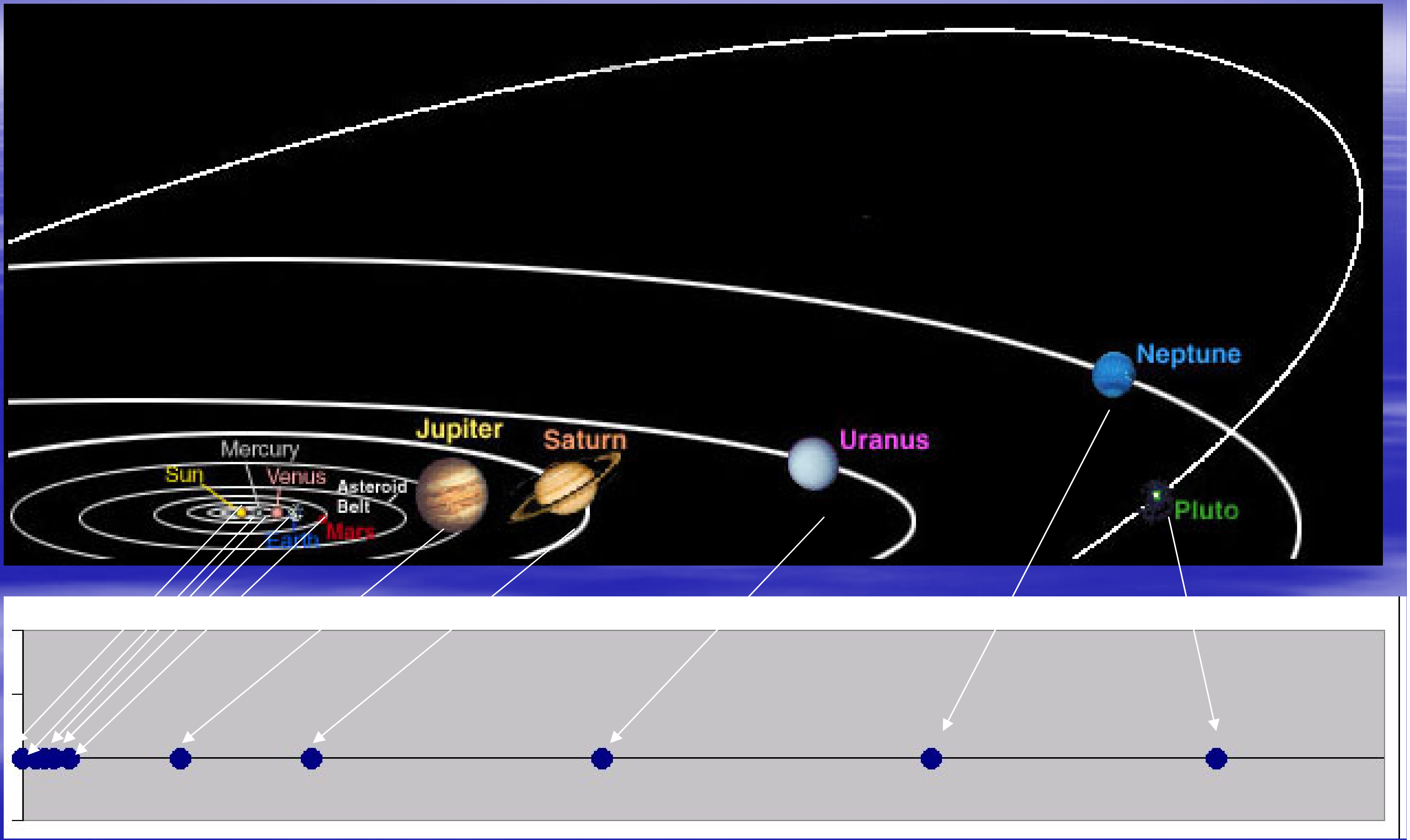
- Some aspects of measuring winds on Venus and other planets are similar to tracking clouds on Earth. *No need for weather forecasts yet!*
- Some of the same cloud tracking methods can be and have been used for planets
- Some techniques used for planetary winds may have use for earth applications
- Finally, foster a greater dialog between terrestrial weather community and planetary scientists
- Venus Atmosphere Workshop in Madison, 30 August 30 – 2 September, 2010.
  - *Pioneer Venus and Venus Express provided winds from a highly eccentric polar orbits from cloud tracking!*
  - *Japan's Venus Climate Orbiter will mimic a geosynchronous satellites (quasi-synchronous with the cloud level circulation)*

Understanding Planetary Atmospheric circulations

- Planets with atmospheres provide a natural laboratory to understand how physical conditions control weather and climate.
  - Can the same models and methods used for terrestrial weather and climate observations and forecasting be used successfully under other conditions as found on the planets?
  - Do we understand the physics and chemistry well and do the numerical models have a good enough representation?

Outstanding Problems in Understanding Planetary Circulations

- How are equatorial “super-rotations” seen on Venus, Jupiter and Saturn produced and maintained?
  – *Superrotation of the Venus atmospheric circulation still cannot be successfully simulated with realistic physics*
- What determines a planet’s atmospheric circulation regime?
- What is the role of the rotation rate of a planet and the jets on planets? – *number of jets on Saturn and Jupiter vs. Neptune*
- Planetary Climates and climate evolution
  – *When and how did the greenhouse effect on Venus originate?*
  – *When did Mars lose surface water?*
  – *Titan’s “methane cycle and greenhouse effect*



Neptune
Jupiter
Saturn
Uranus
Mercury
Sun
Venus
Asteroid
Belt
Earth
Mars
Pluto

Diversity of Planetary conditions External:

- Insolation
  - (Venus to Pluto)
- Seasons
  - None to very long
- Rotation rate
  - Slow rotators (Venus, Titan) and fast rotators (Jupiter, Saturn, Neptune, Uranus)

Diversity of Planetary Conditions

Atmospheric properties

Gravity

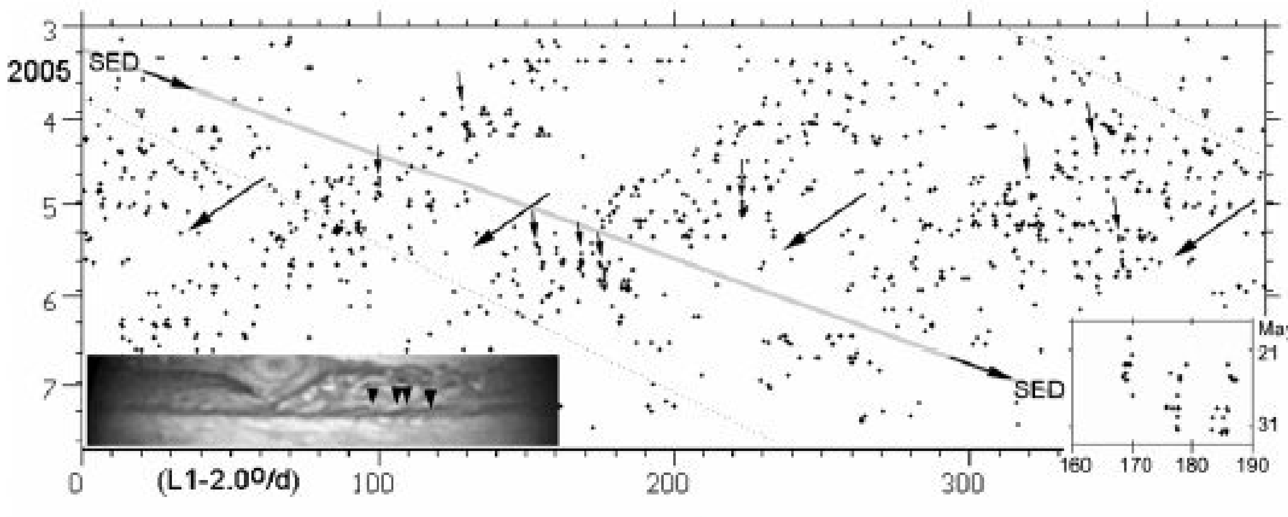
- Pressure (90 bars on Venus, 1.5 bars on Titan and ~ 10 mb on Mars)
- Composition and Clouds
- Surface Properties and Presence of Volatiles
  - Frozen carbon dioxide and water ice on Mars, hydrocarbons on Titan, Sulfur on Venus?

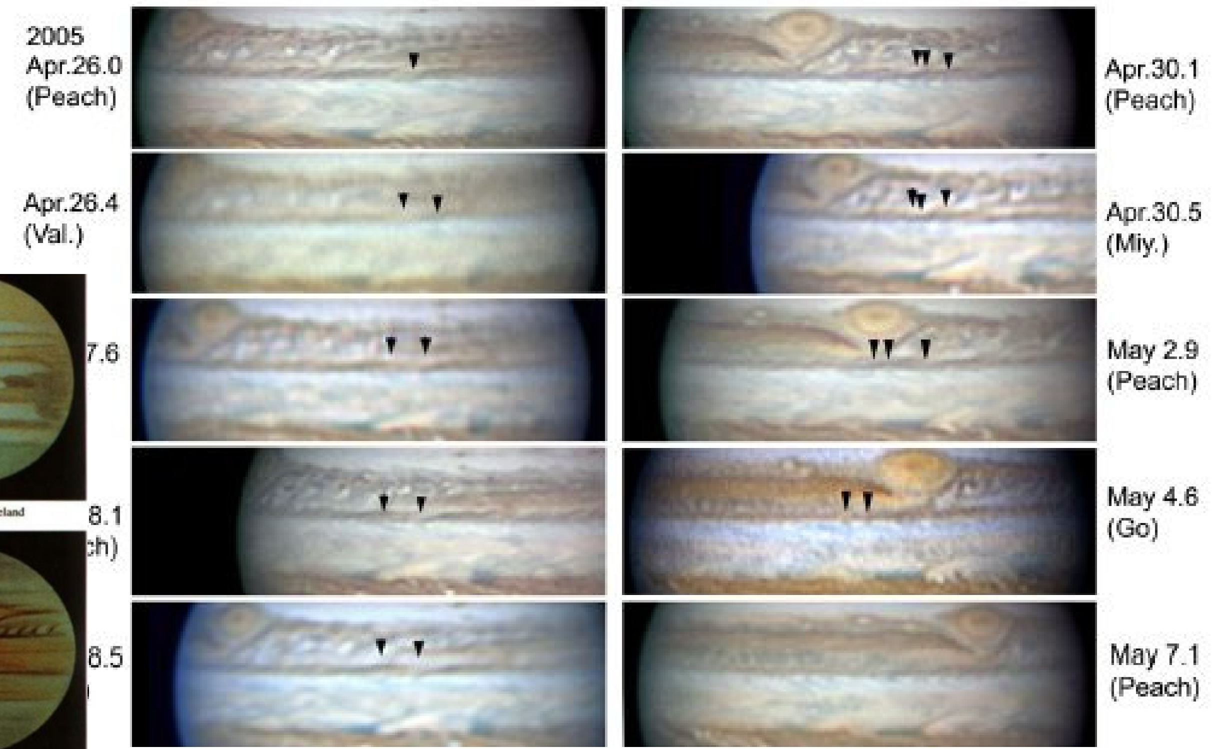
First application of cloud tracking was for winds on Jupiter!

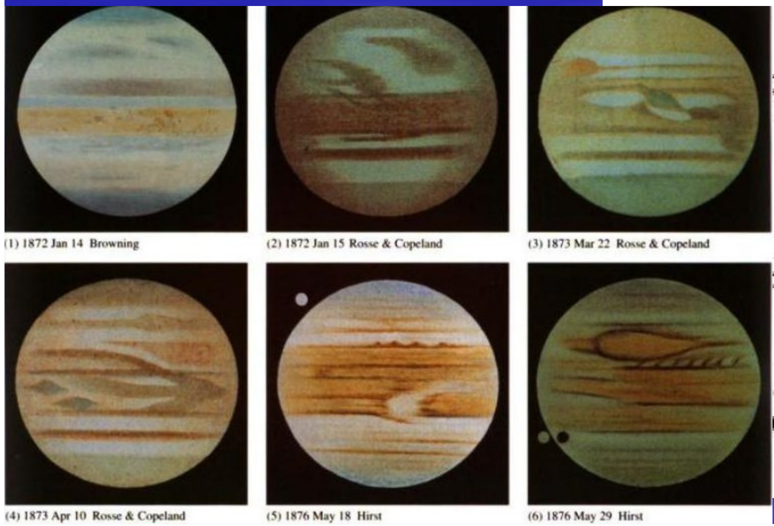
Jupiter wind velocities from position measurements of spots as has been done since 1860s.

Below are some color drawings of Jupiter from 1870s

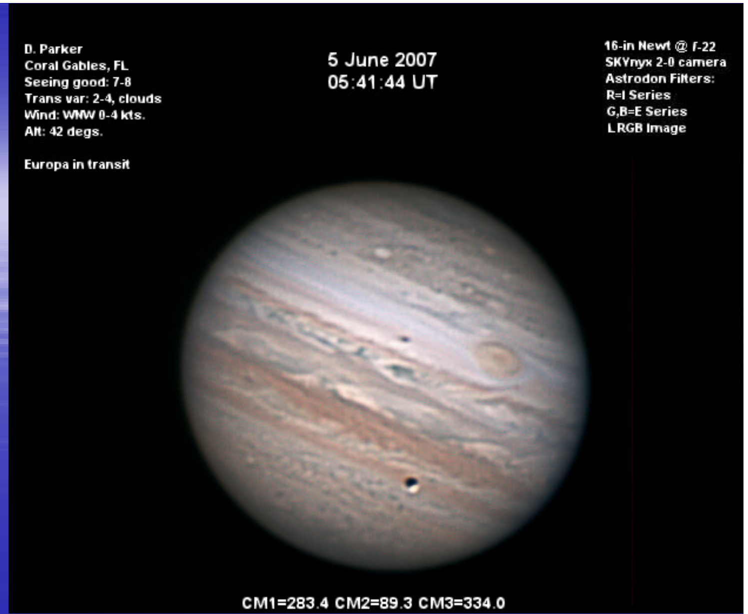
Below: A series of these strip-maps in colour showing the motion of the cluster at ~-2.6 to -2.0°/day, within a band of activity that was moving at ~-3.5°/day, *(Supplementary On-line Figure 8b).*



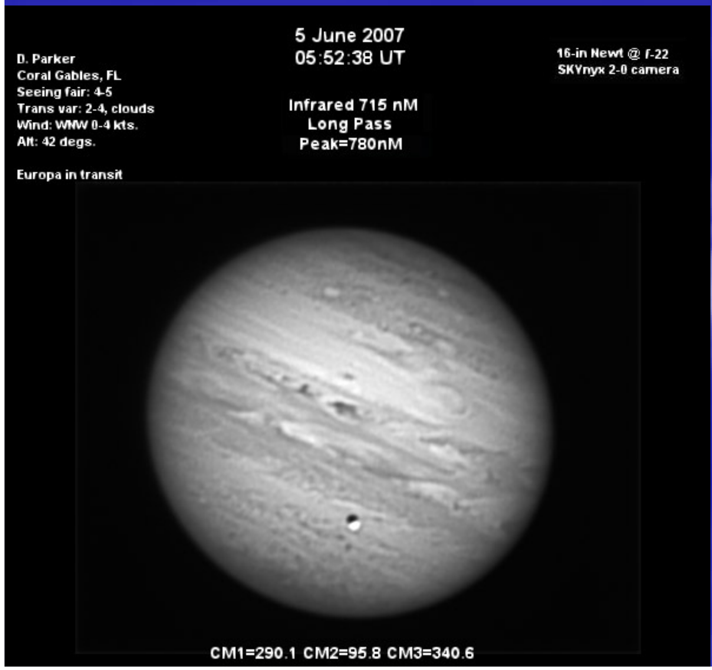




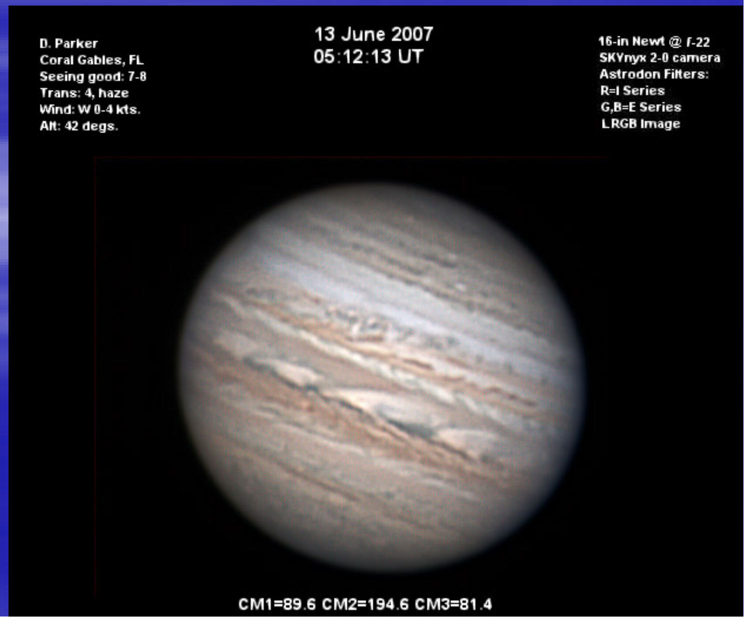
Amateur imaging capabilities have improved significantly and their observations are critical for Jupiter now!



Spots on Jupiter are long lived to be followed for days and weeks.



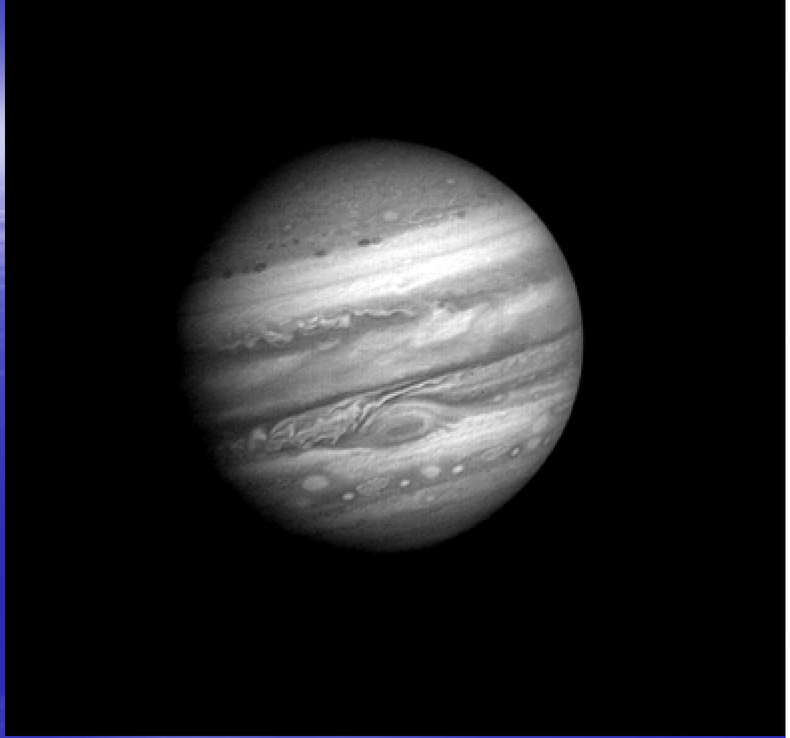
Measurement of their longitudinal position over time provided the first indication of the East-West jets on Jupiter and later Saturn



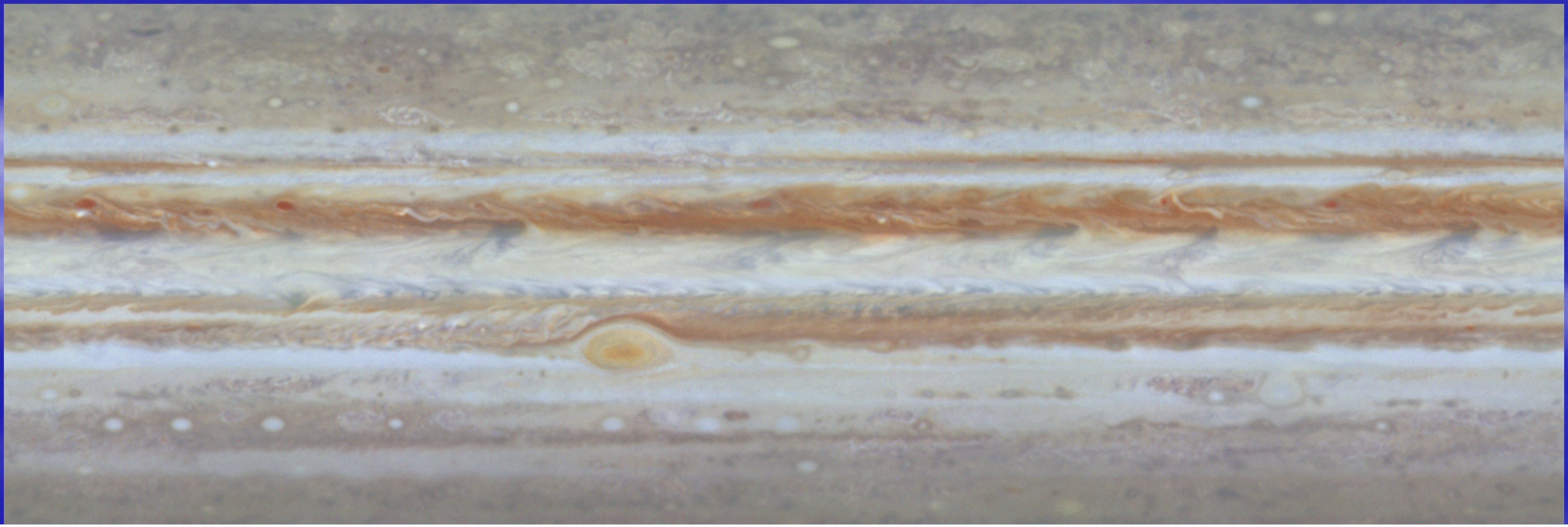
The ground based observations of East-West currents on Jupiter were measured with greater spatial resolution from Voyager 1 and Voyager 2 Data using different tracking methods. *However, the meridional component, being much weaker, is still poorly known*.

The approach leg of the spacecraft provides sun-synchronous view of the outer planets

Voyager 1 "Blue Movie"

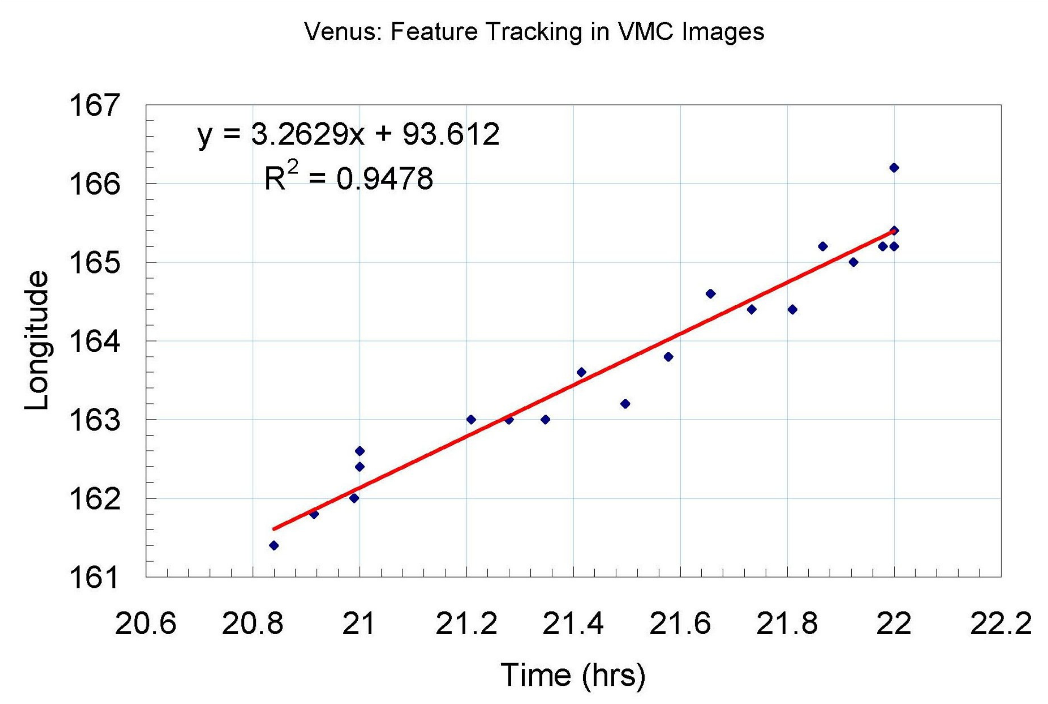


Global maps of Jupiter from Cassini Fly-by during approach – December 2000



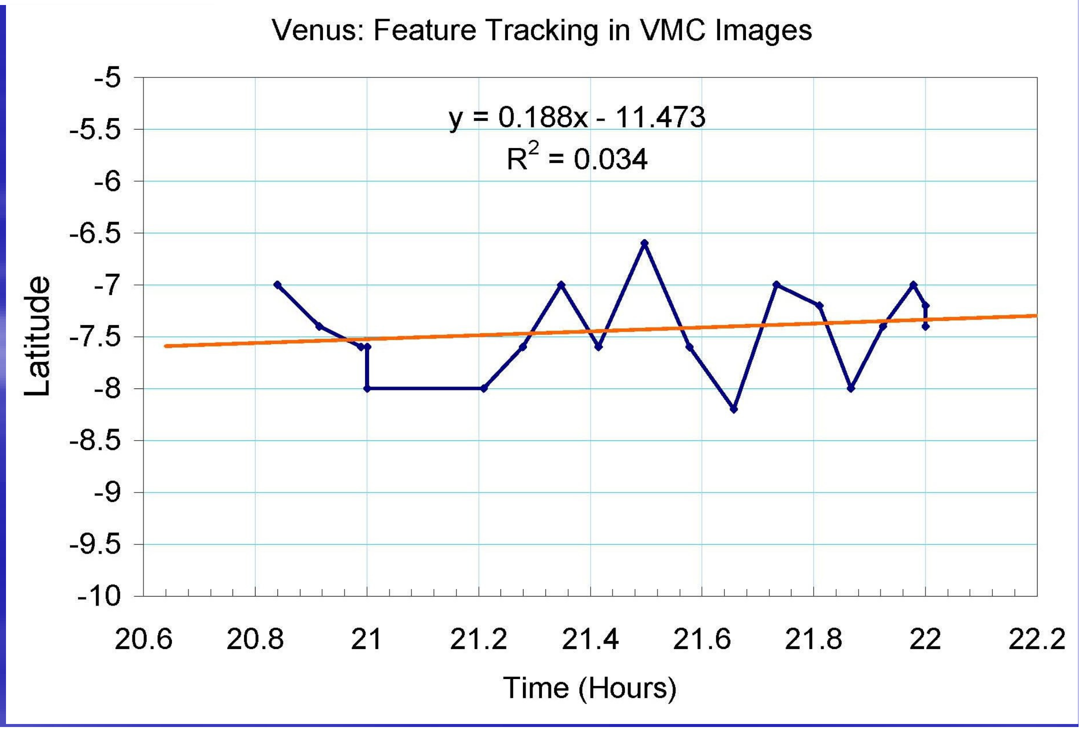
Cloud Tracking: 1. Position Measurements over time

- Relevant issues:
  - Image resolution requires commensurate time interval. *Quality of navigation – when no landmarks!*
  - For ground based images, the spatial resolution is nominally ~ 0.1 to 1 arc second or ~ 1500 km per pixel at Jupiter! *Spacecraft data constrained by fly-by or orbit geometry and data rates. Have to use image pairs or triplets.*
  - Requires long lived features to get meaningful measurements since the drift rates are ~ tens m/s



For long lived clouds, velocities can be determined from multiple position measurements.

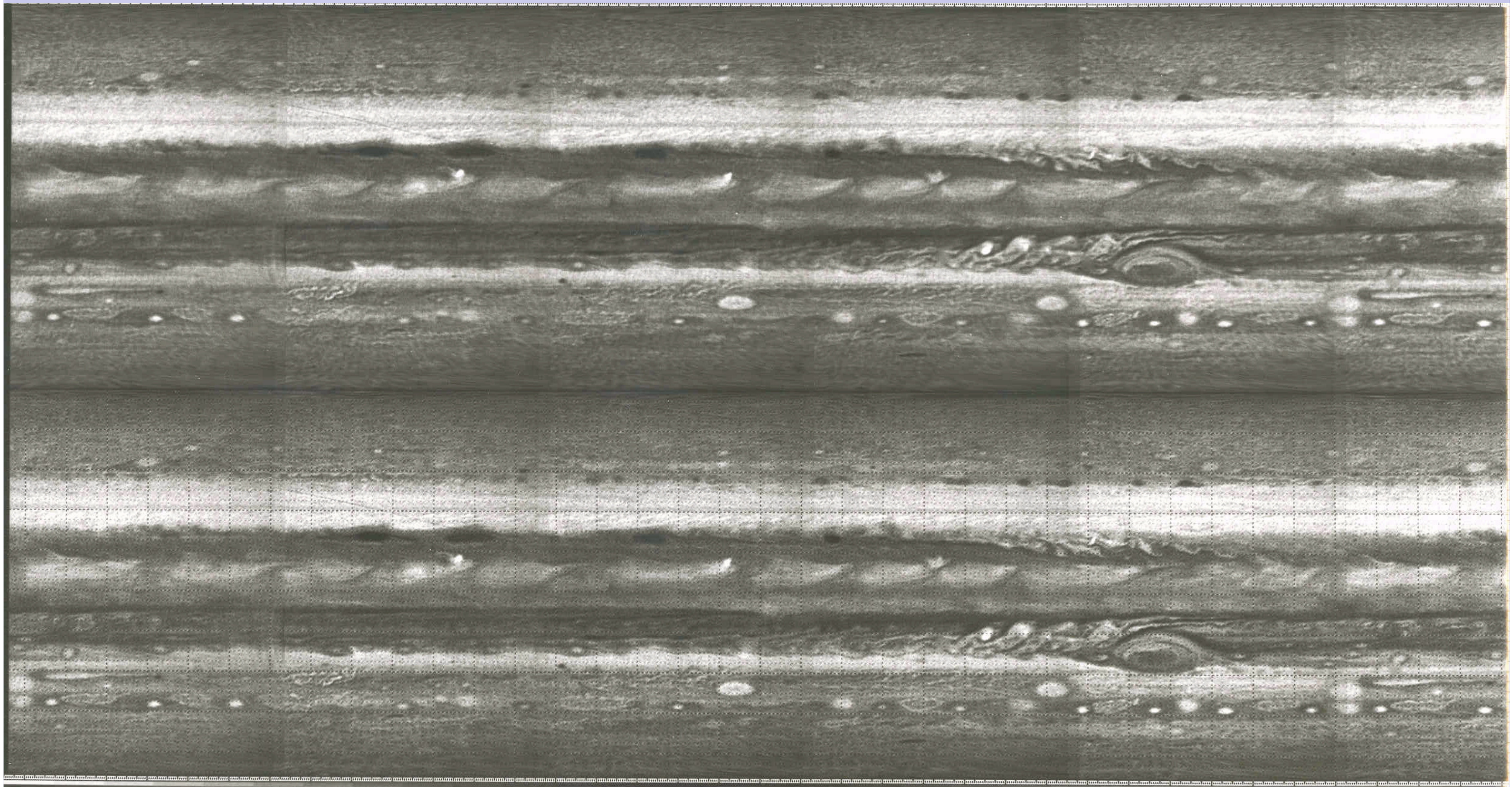
On Jupiter "spots" can be tracked for weeks and months



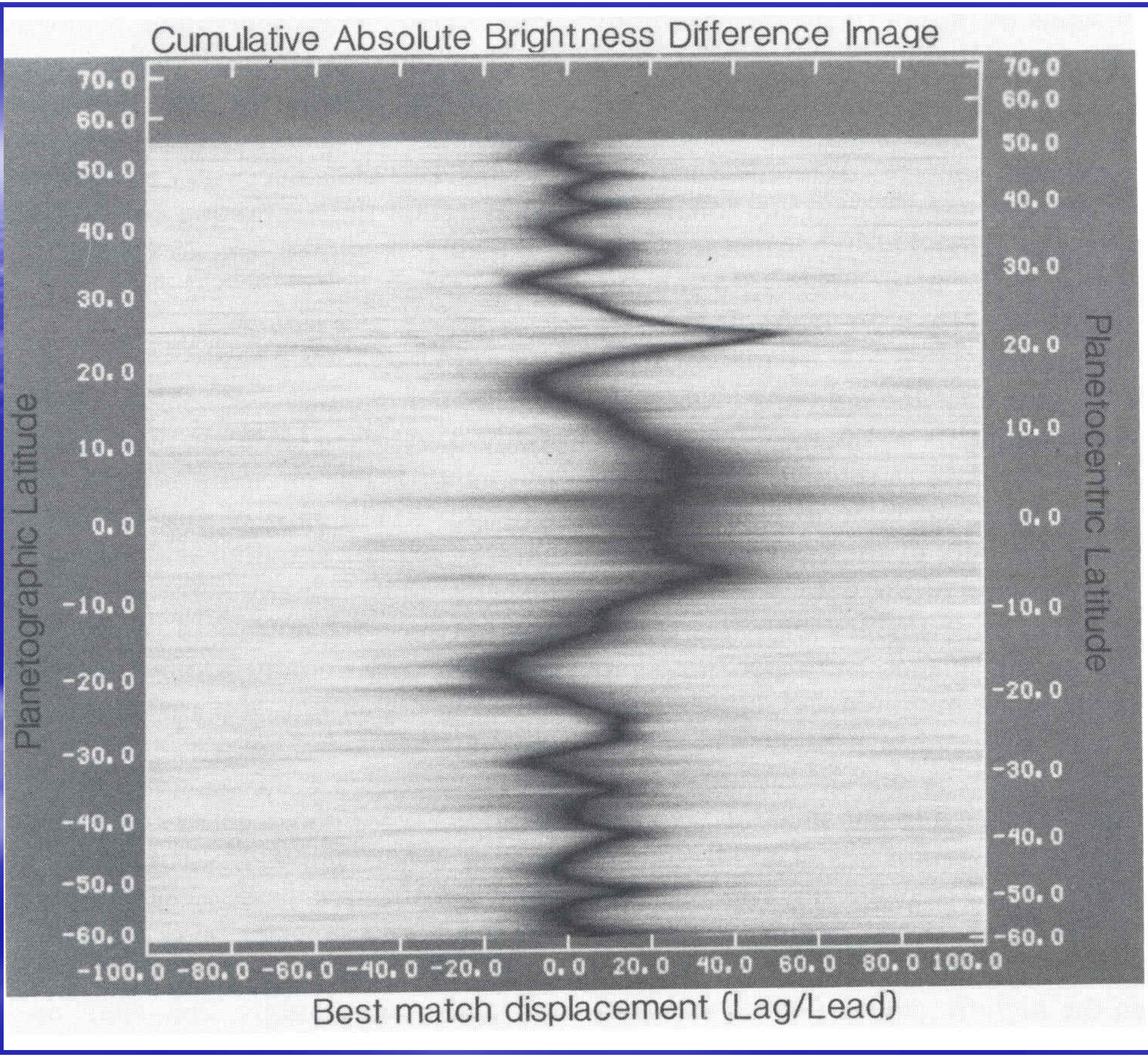
Cloud Tracking: 2. Determining Zonal Average circulations from longitudinal brightness distribution from global maps

- Works for Jupiter and Saturn
- No Meridional Flow obtained
- Does not work for other planets
  - Venus: *meridional component large and maps cannot be produced quickly from a single orbiter compared to the cloud life-time*
  - Mars: *Imaging does not emphasize atmospheric imaging, cloud tracking feasible only in polar latitudes*
  - Uranus: Not much detail in the images!
  - Neptune: Little small scale detail but more clouds than Uranus
  - Titan: *Not enough imaging coverage from Cassini for global maps (reflected solar and infrared)*

Rotation 6 - Voyager 1 Blue Images

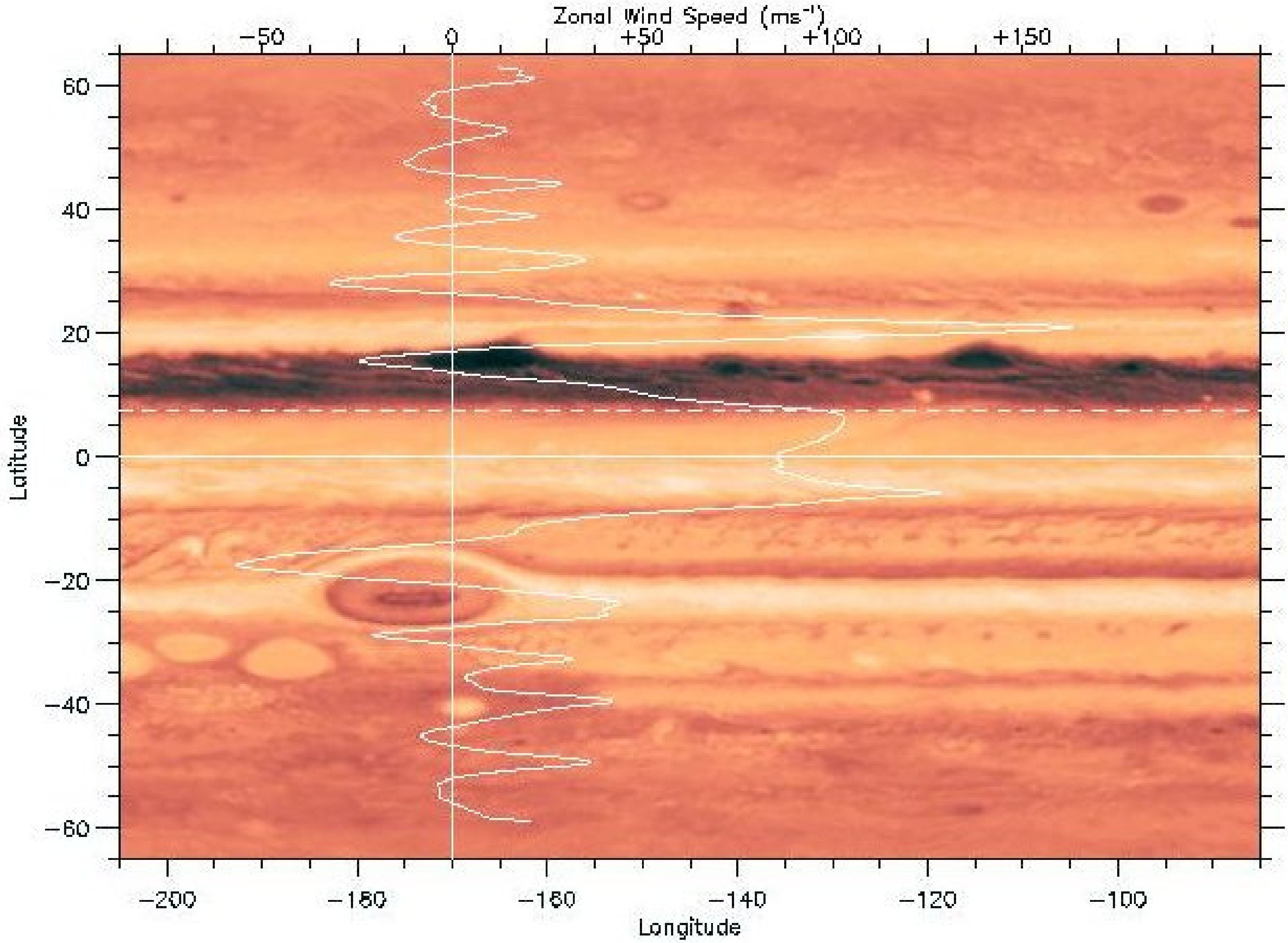


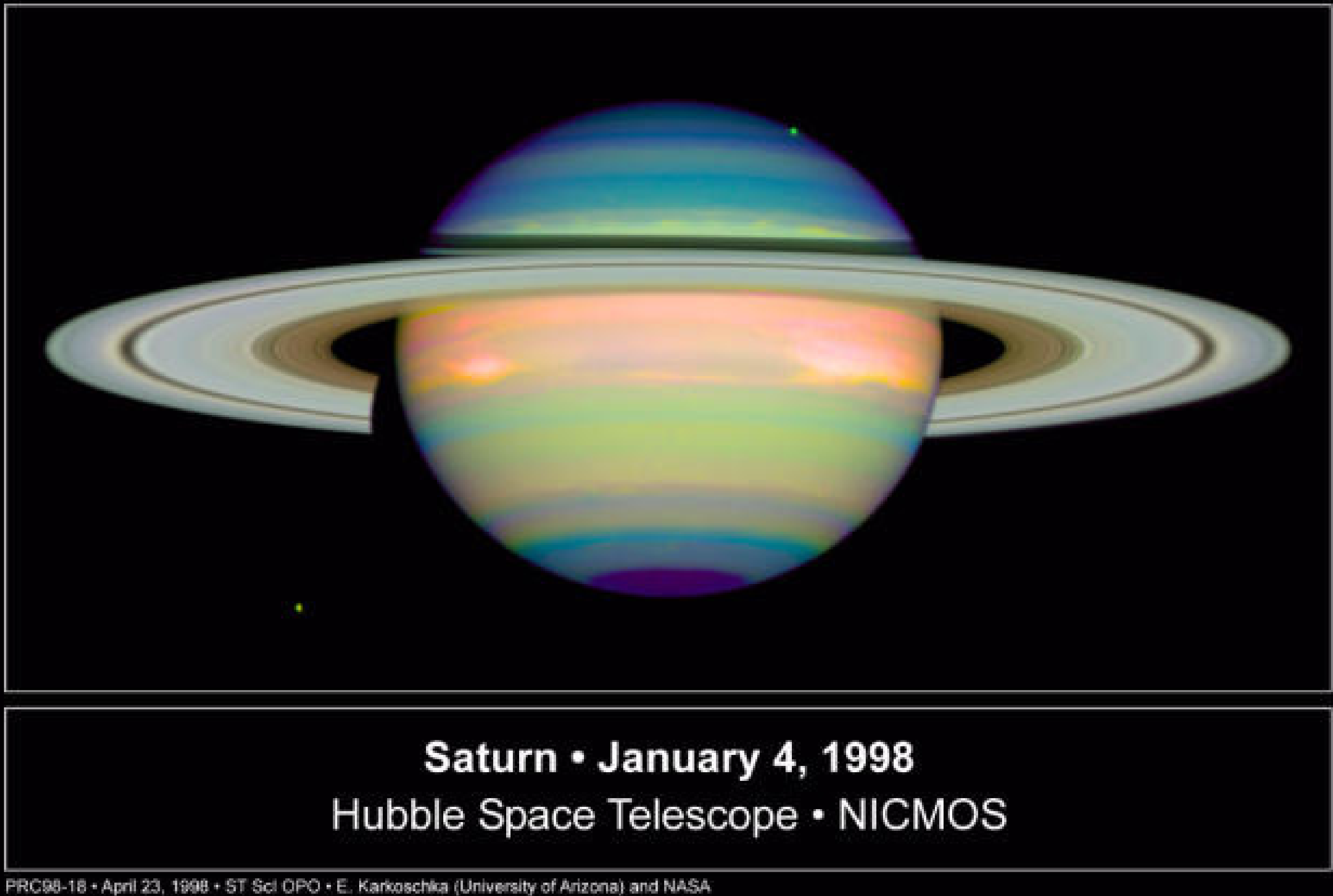
Exploiting the nature of the zonal currents on Jupiter and low meridional speeds to obtain better zonal average values of the jet speeds by using an entire longigtude of brightness data for tracking.



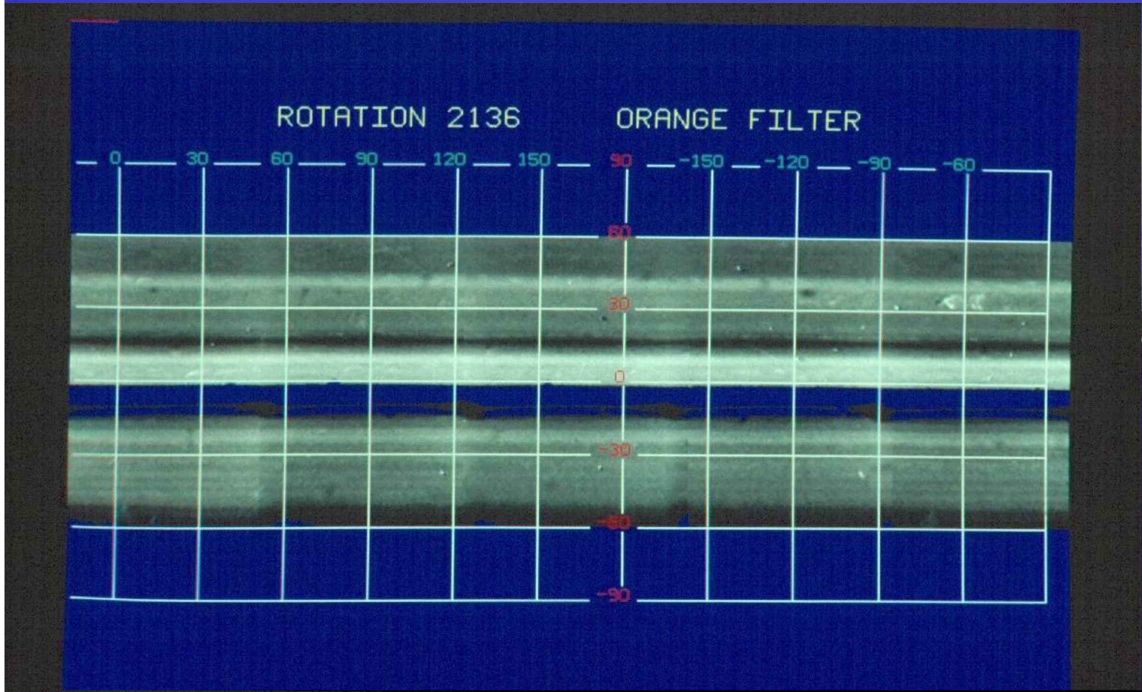
Cumulative Absolute Brightness Difference Image
Planetographic Latitude
Planetocentric Latitude
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-100.0 -80.0 -60.0 -40.0 -20.0 0.0 20.0 40.0 60.0 80.0 100.0
Best match displacement (Lag/Lead)

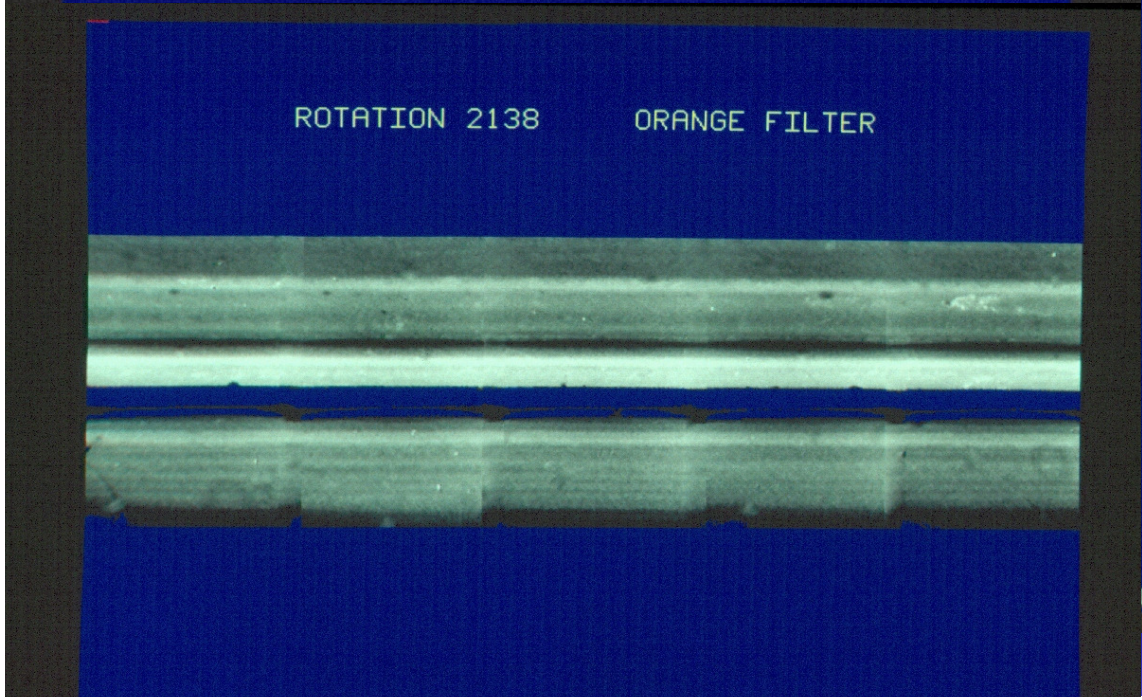
Cloud Level East-West Winds on Jupiter (*Limaye, Icarus, 1986*)

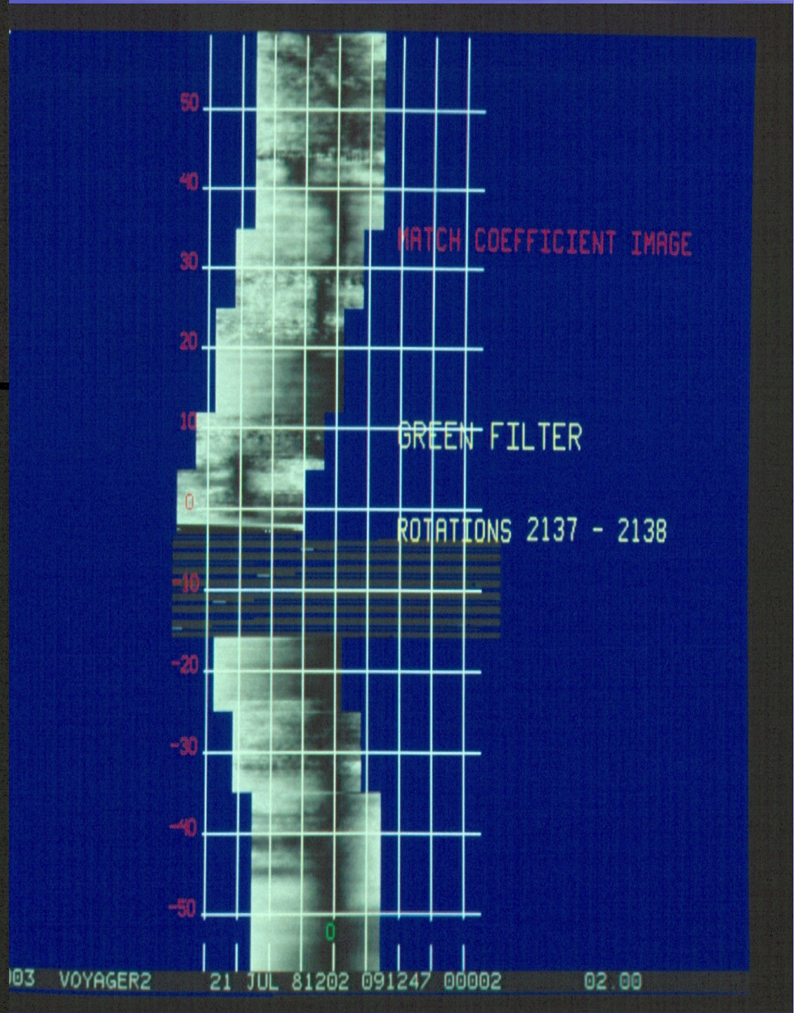




Brightness matching technique also applied successfully with global maps of Saturn from Voyager multi-filter imagery

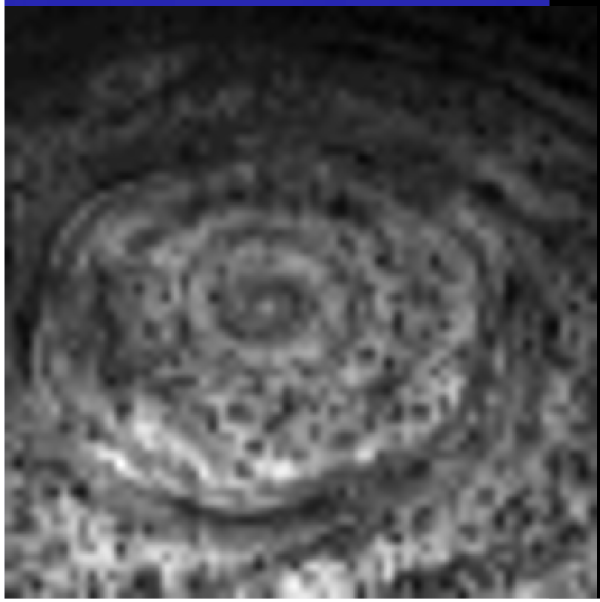

ROTATION 2136 ORANGE FILTER
0 30 60 90 120 150 90 -150 -120 -90 -60
60 30 0 -30 -60 -90


ROTATION 2138 ORANGE FILTER

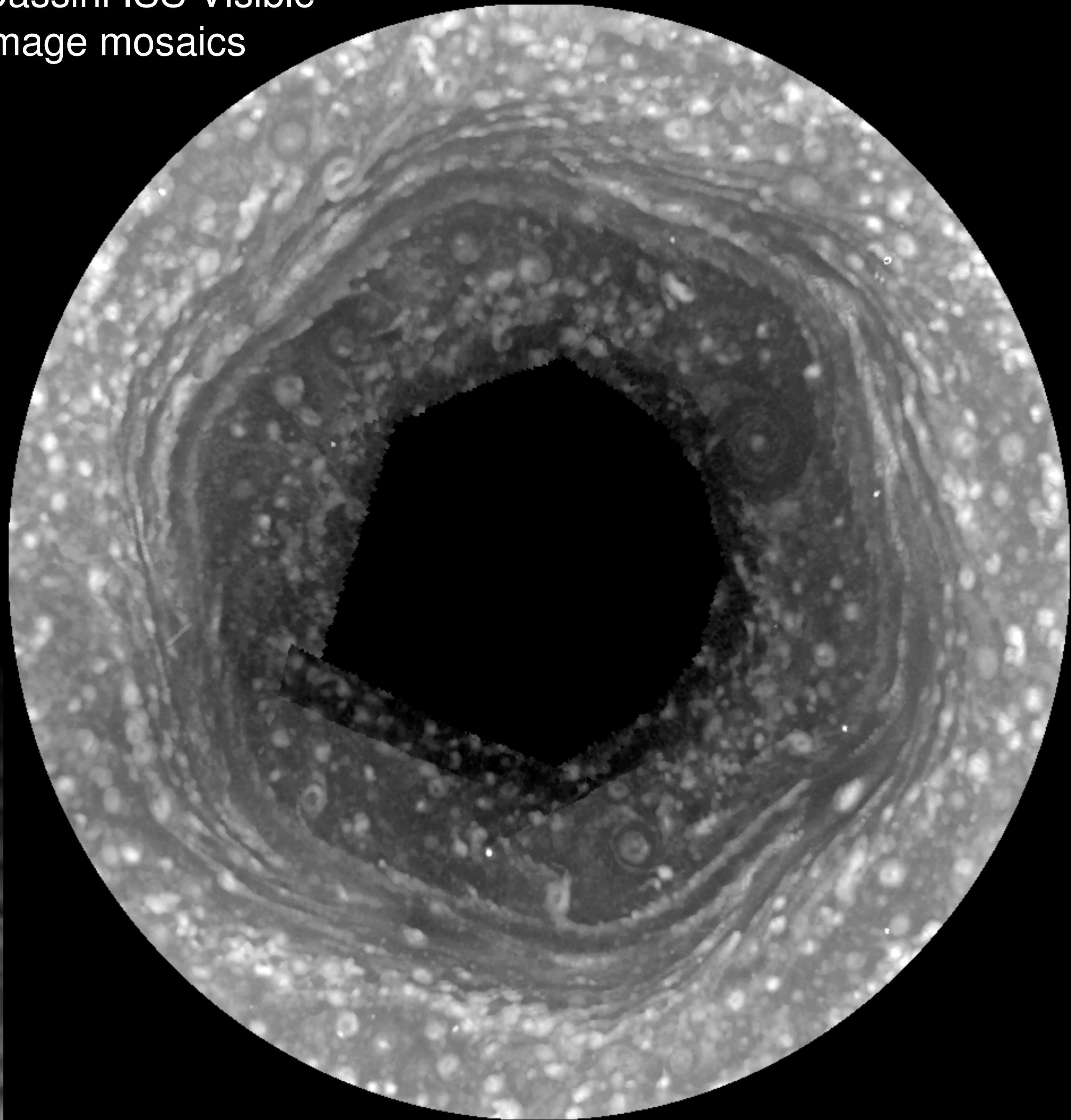

MATCH COEFFICIENT IMAGE
GREEN FILTER
ROTATIONS 2137 - 2138
50 40 30 20 10 0 -10 -20 -30 -40 -50
VOYAGER2 21 JUL 81202 091247 00002 02.00

Hexagon on Saturn –
Barotropic instability ?

Peering below the visible clouds: Infrared view of Saturn's South pole



Cassini ISS Visible image mosaics



Cloud tracking: 3. Particle Velocimetry

- New approach to determining atmospheric flow with unprecedented results - applied successfully to Jupiter images

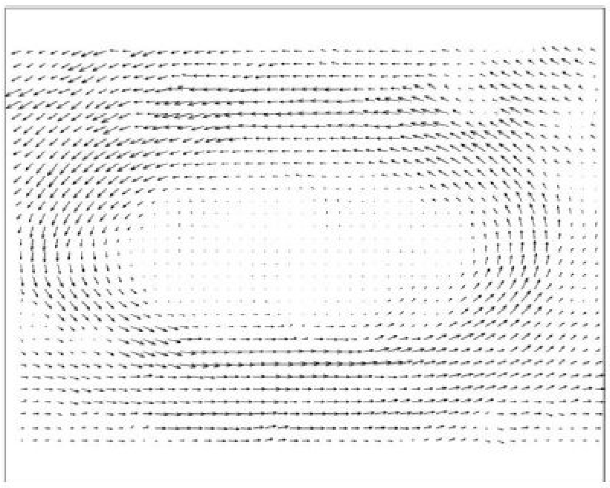


Fig. 7. Horizontal velocity field obtained via CIV using the images shown in Fig. 6. The field over which vectors are computed corresponds directly to the images shown in the previous figure.

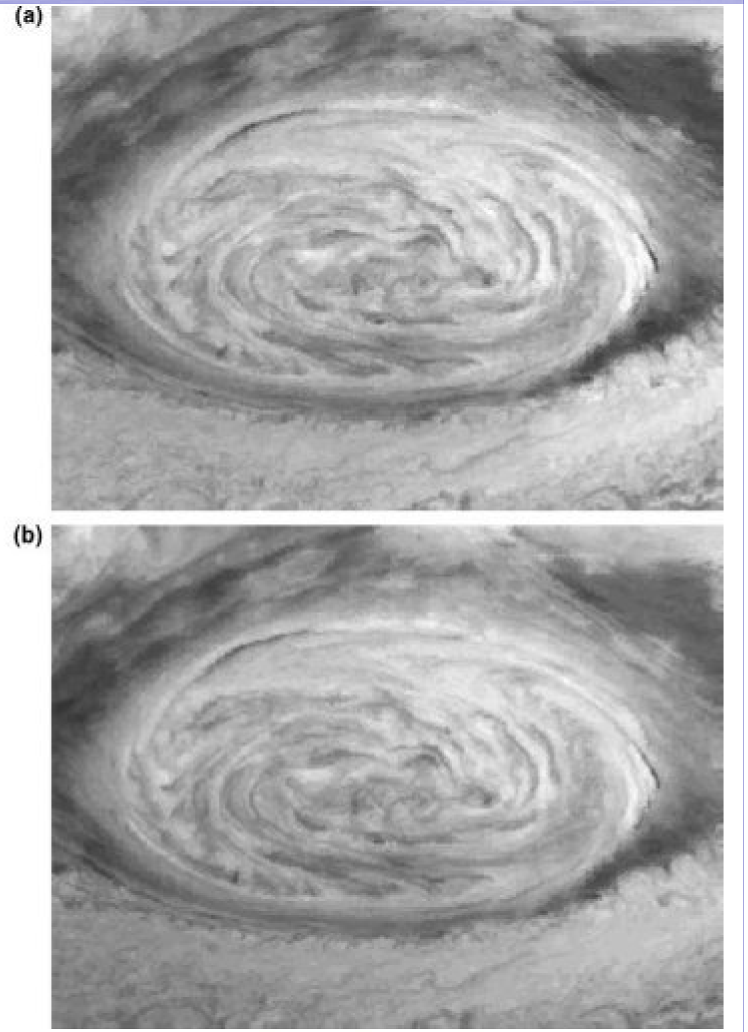


Fig. 6. A pair of images (http://photojournal.jpl.nasa.gov/animation/PIA01083) taken in the near-infrared (756 nm) by the Galileo Solid State Imager of Jupiter's Great Red Spot, separated in time by one jovian rotation.

Advected Corrected Correlation Image Velocimetry: Iterative use of PIV

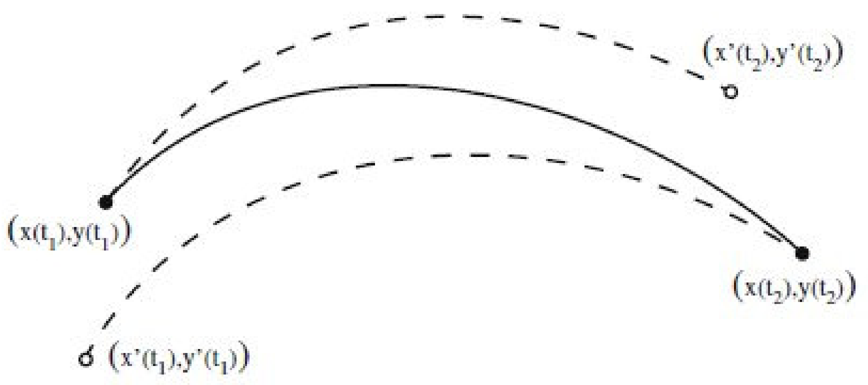


Fig. 8. ACCIV refinement of the trajectory followed by a feature between time t_1 and time t_2. The upper dashed path is the trajectory that leads from the actual (solid circle) location of the tie-point in the first image $(x(t_1), y(t_1))$, to its erroneous location (open circle) in the second image $(x'(t_2), y'(t_2))$ as computed numerically by forward integration from t_1 to t_2 with the assumed velocity field. The lower dashed path is the trajectory that leads back from the actual location (solid circle) of the tie-point in the second image, $(x(t_2), y(t_2))$ to its erroneous location (open circle) in the first image $(x'(t_1), y'(t_1))$ as computed numerically by backward integration from t_2 to t_1 with the assumed velocity field. The distances between the actual and erroneous locations are measures of the *correlation uncertainty*. The solid path connecting the actual locations of the tie-points at times t_1 and t_2 is the linear interpolation of the two dashed trajectories (see Appendix A.6).

May be useful for winds for terrestrial cyclone imagery?

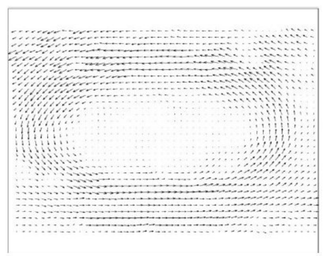
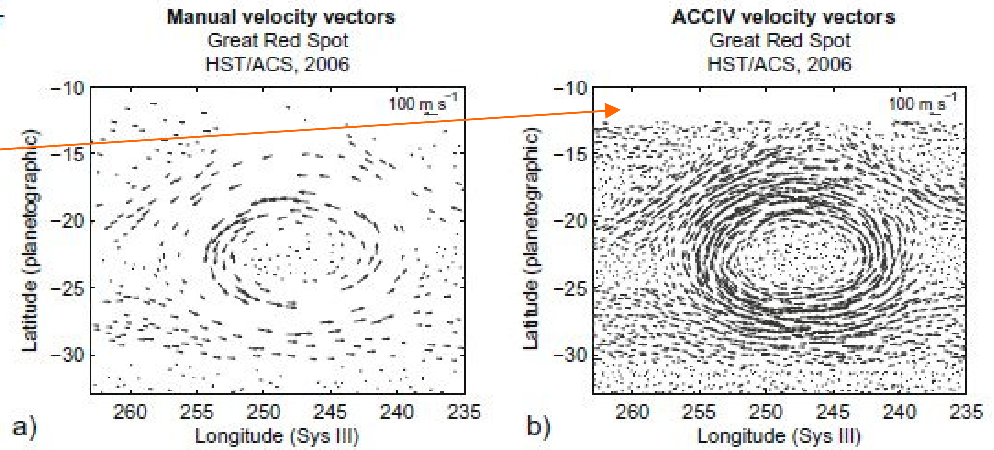
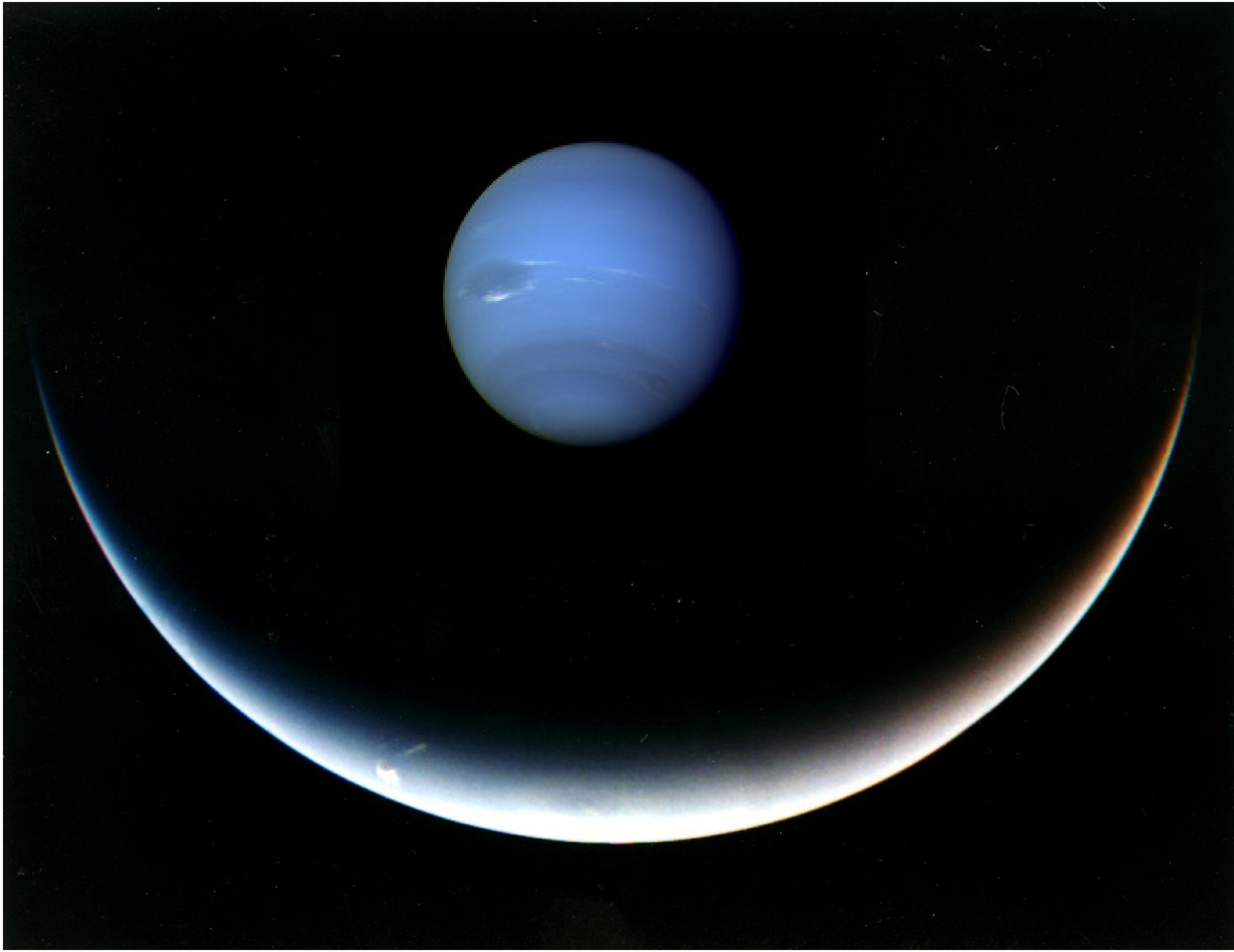


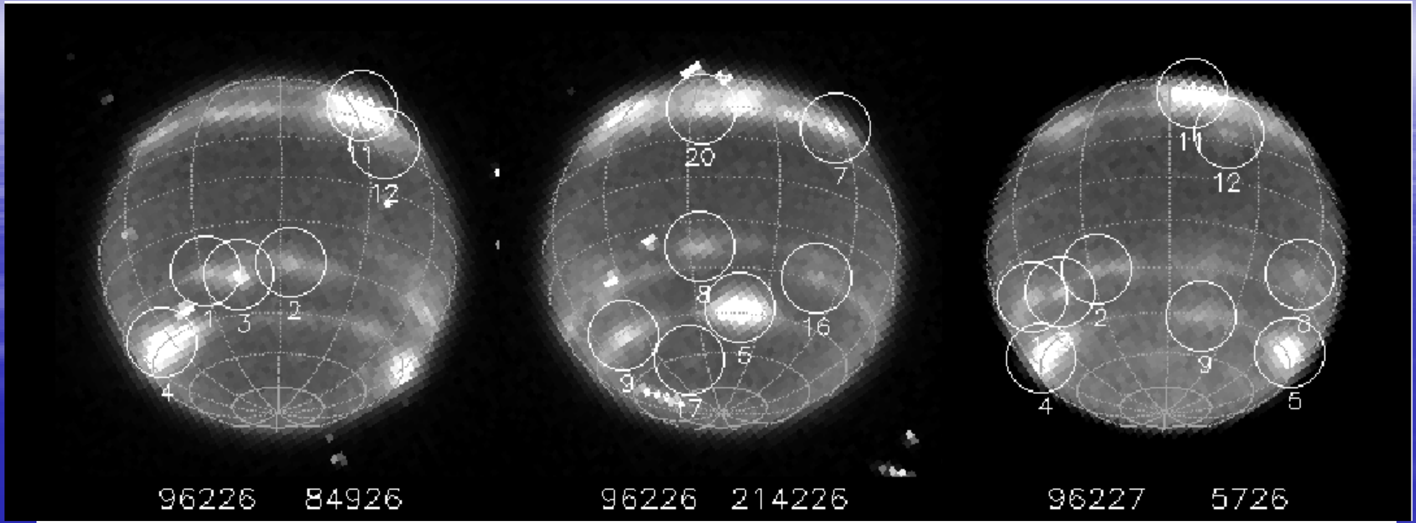
Fig. 7. Horizontal velocity field obtained via CIV using the images shown in Fig. 6. The field over which vectors are computed corresponds directly to the images shown in the previous figure.

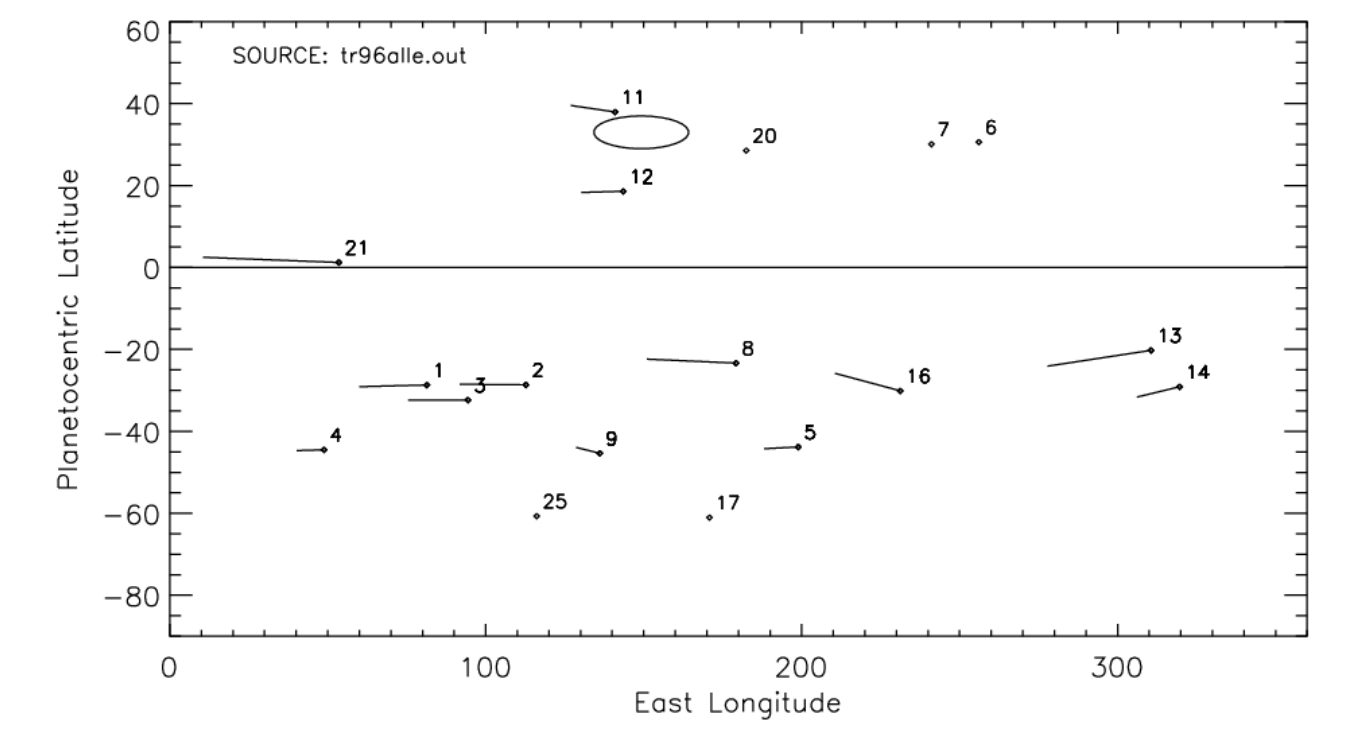
Iterative use can yield a lot of vectors





Neptune: Cloud-Tracked Winds from HST

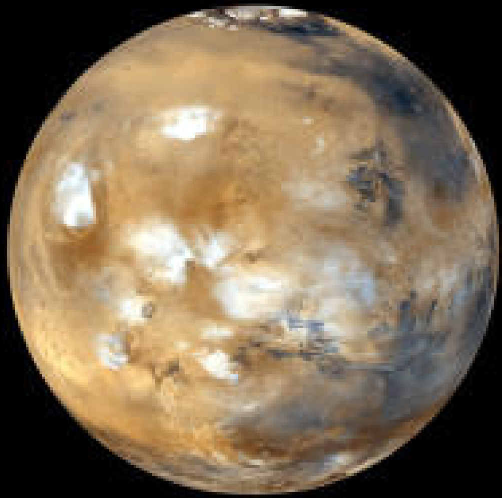




Cloud Tracking on Mars

View of Earth from Galileo Orbiter

Global composite view
from Mars Global Surveyor
Images from polar orbit

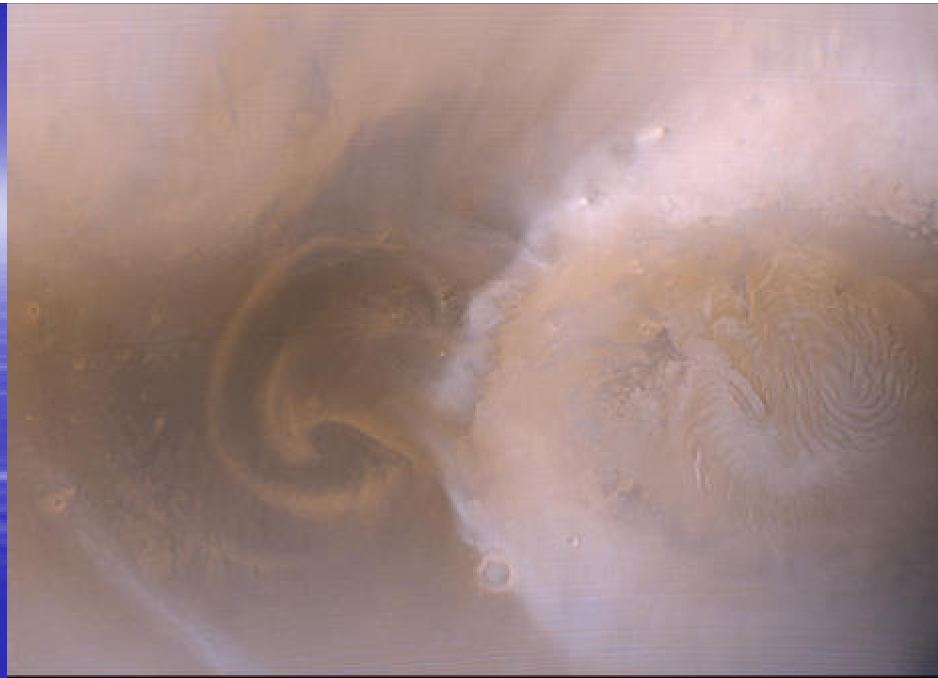


Far fewer clouds on Mars !

Relative size of Earth and Mars

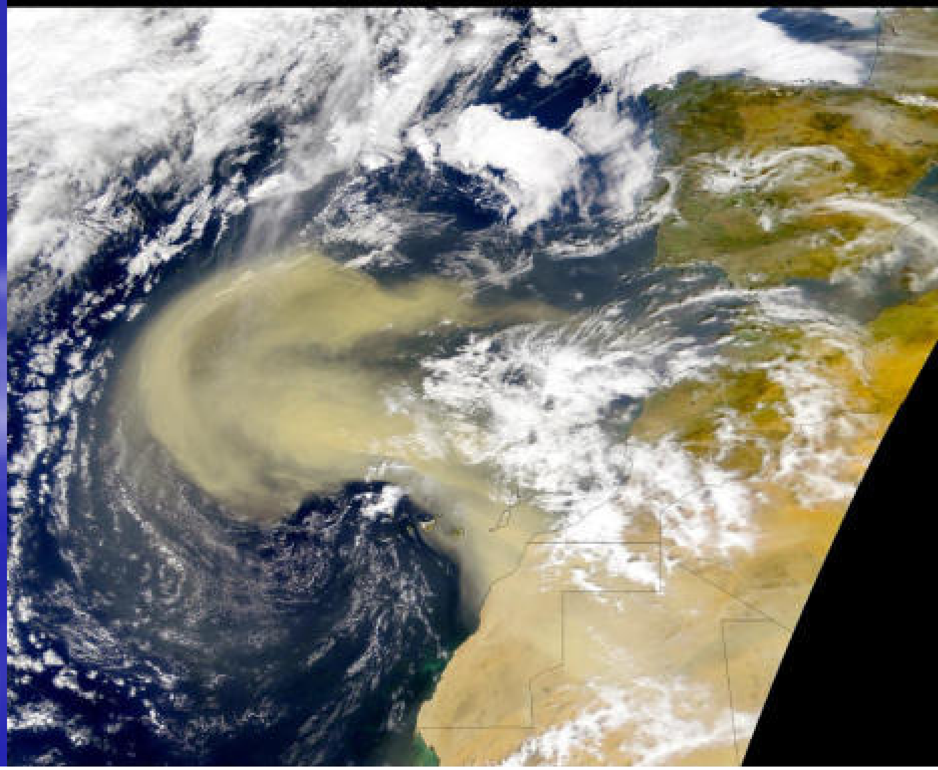
Martian Dust Storm near the Northern Pole

(Mars Global Surveyor)



A lot similarities in atmospheric processes on Mars and Earth despite compositional and surface pressure differences.

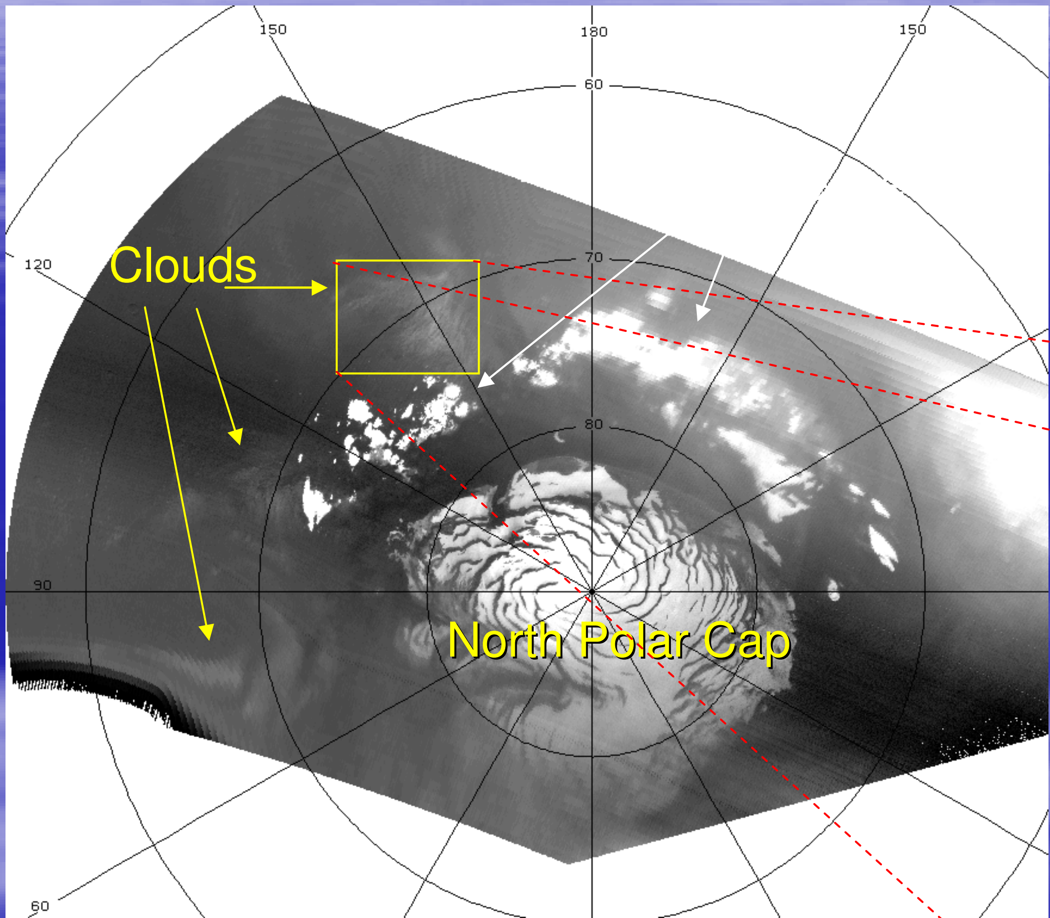
Overlapping coverage over a short term at low latitudes not available yet from spacecraft



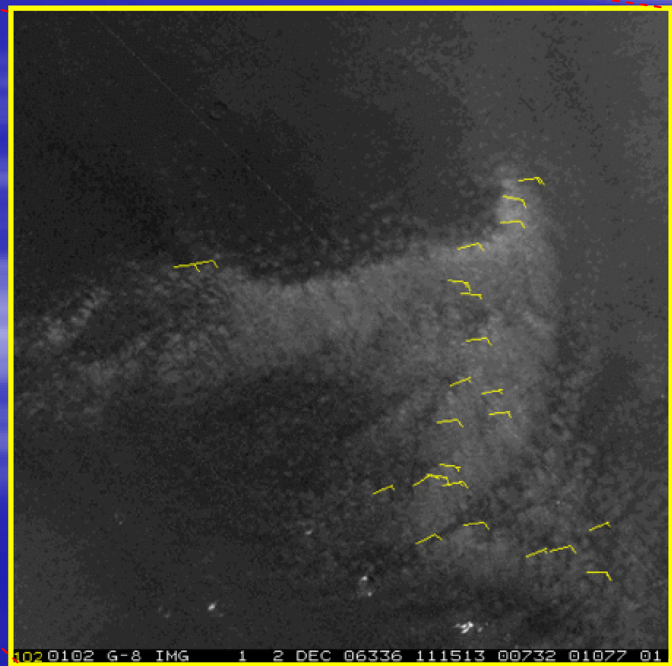
Cyclones, dust devils commonly observed on Mars.

Dust storm off Sahara on Earth from MODIS

High latitude winds on Mars



- Wind speeds up to about 7 ms^{-1} in this example.
- Winds slower than 3 ms^{-1} are discarded (geolocation errors)



Venus Atmospheric Circulation: Observations

- First reported by Boyer and Guerin from telescope images *("4-day wind")*
- Doppler Spectroscopic limb observations *(Traub and Carleton)*
- Earth Based Doppler tracking of Atmospheric Entry Probes (Venera 6 –15, Pioneer Venus Large and Small Probes)
- VLBI tracking VeGa 1 and VeGa 2 constant level balloons
- Tracking features in images/maps from spacecraft (UV, Near IR)
- Indirect inferences from thermal structure – Balanced flow
- Surface wind from anemometers on Venera probes
- Indirect inferences from wind produced patterns on the Venus surface (Magellan radar imagery)

Venus:Current and Future Atmospheric Circulation Data

- Venus Express is currently returning images daily in four filters from an eccentric, 24-hr polar orbit, providing good views of the southern polar region.
- Akatsuki (Venus Climate Orbiter) will provide reflected UV and infrared images from an eccentric near equatorial orbit (30 hour period) quasi-synchronous with the “4-day” circulation
- NASA’s SAGE Entry probe in a competitive selection process
- Several Discovery Mission Proposals (NASA)
- Venera – D Mission from Russia
- European Venus Explorer (Balloon mission)
- Ground based imaging (NIR imaging)

Venus Atmospheric Circulation: *Initial Expectations vs. Reality*

- Early expectations were circulation to be thermally driven between the day-side and night-side due to the slow rotation of the solid planet
  - *only found in the mesosphere (85 – 140 km)*
- High surface temperature and pressure at the surface, particularly near the poles were a major surprise
- Little difference in day-night temperature difference

What do we know?

- Bulk of the atmosphere (below ~ 95 km) rotates faster in the same direction as the solid planet with a weak poleward flow at all observed levels.
- strength is variable ~ months.
- circulation organized into two hemispheric vortices centered over each pole with mid latitude jets near 45° latitude, weak asymmetry
- Day-Night flow above ~ 85 km. Circulation seems to vary in strength on a time scale of ~ one or two years
- Solar thermal tides detected from day-side observations. *What role do they play in the atmospheric circulation?*

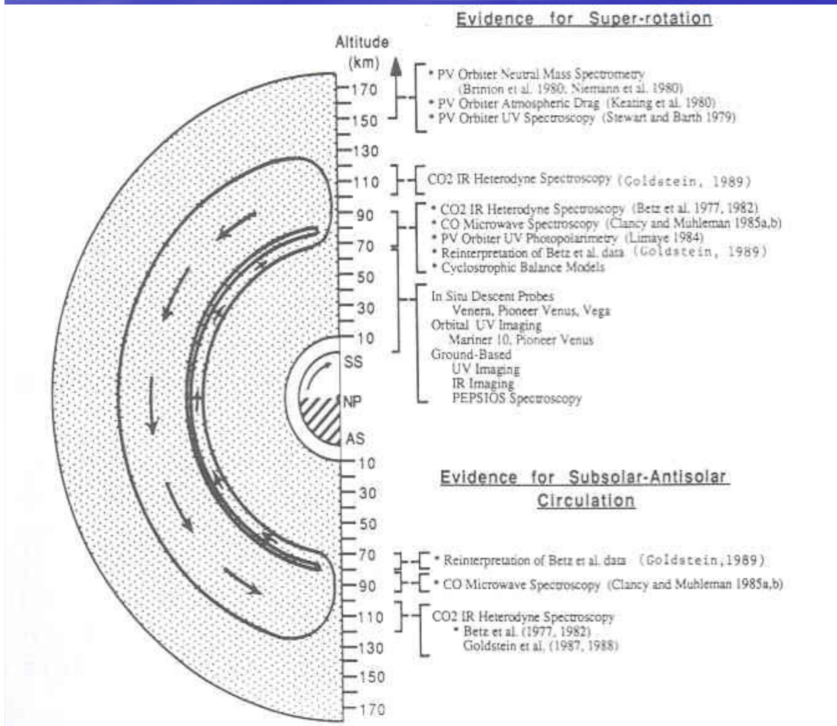


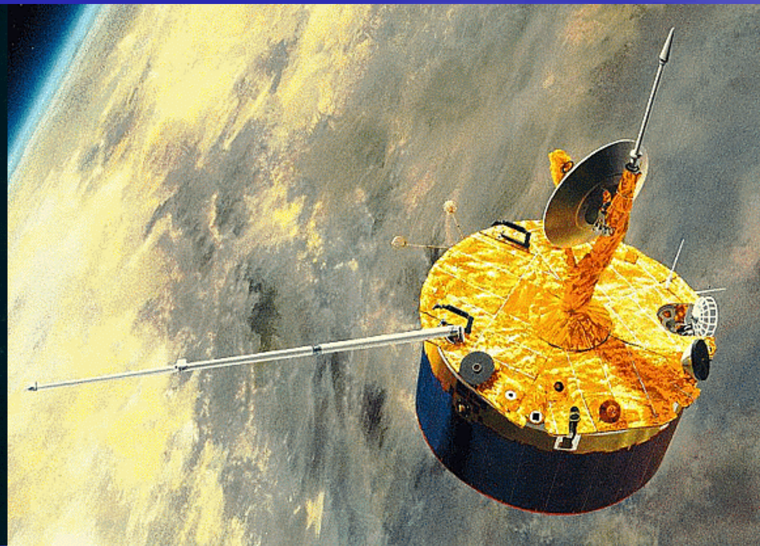
Figure 6. Dynamical regions of Venus' mesosphere and thermosphere (figure from Goldstein 1989).

Horizontal Structure of the Circulation

Feature Tracking in Spacecraft Images

- Mariner 10 Fly-By (~ 3.5 days in 1974)
- About five useful imaging “seasons” of about 100 days each over six year period from Pioneer Venus Orbiter (1979 - 1983)
- Limited Galileo Visible (48 hours) and Near IR imaging (~ 10 hours)
- *Venus Express Observations from April 2006 onwards*
- *Venus Climate Orbiter will arrive at Venus in December 2010*

Mariner 10 Television Images

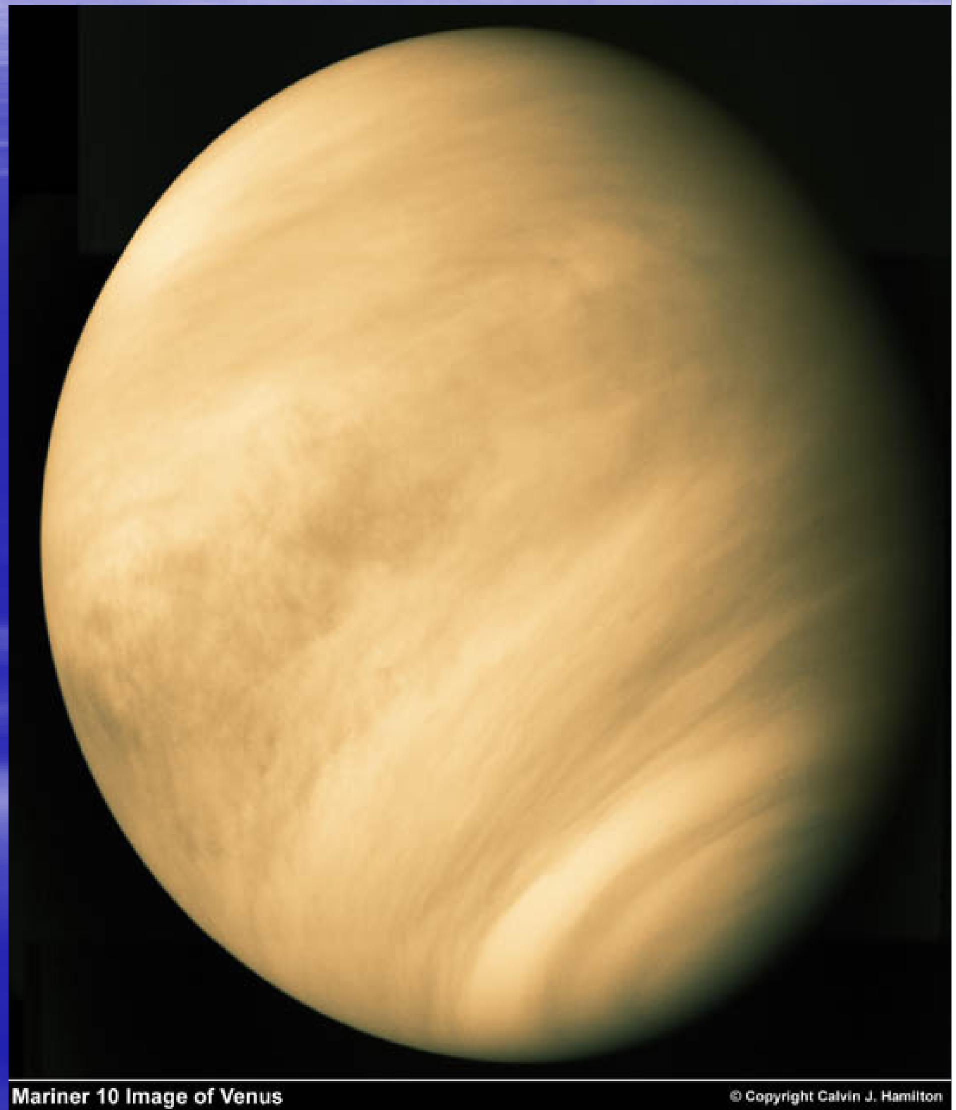


Pioneer Venus OCPP

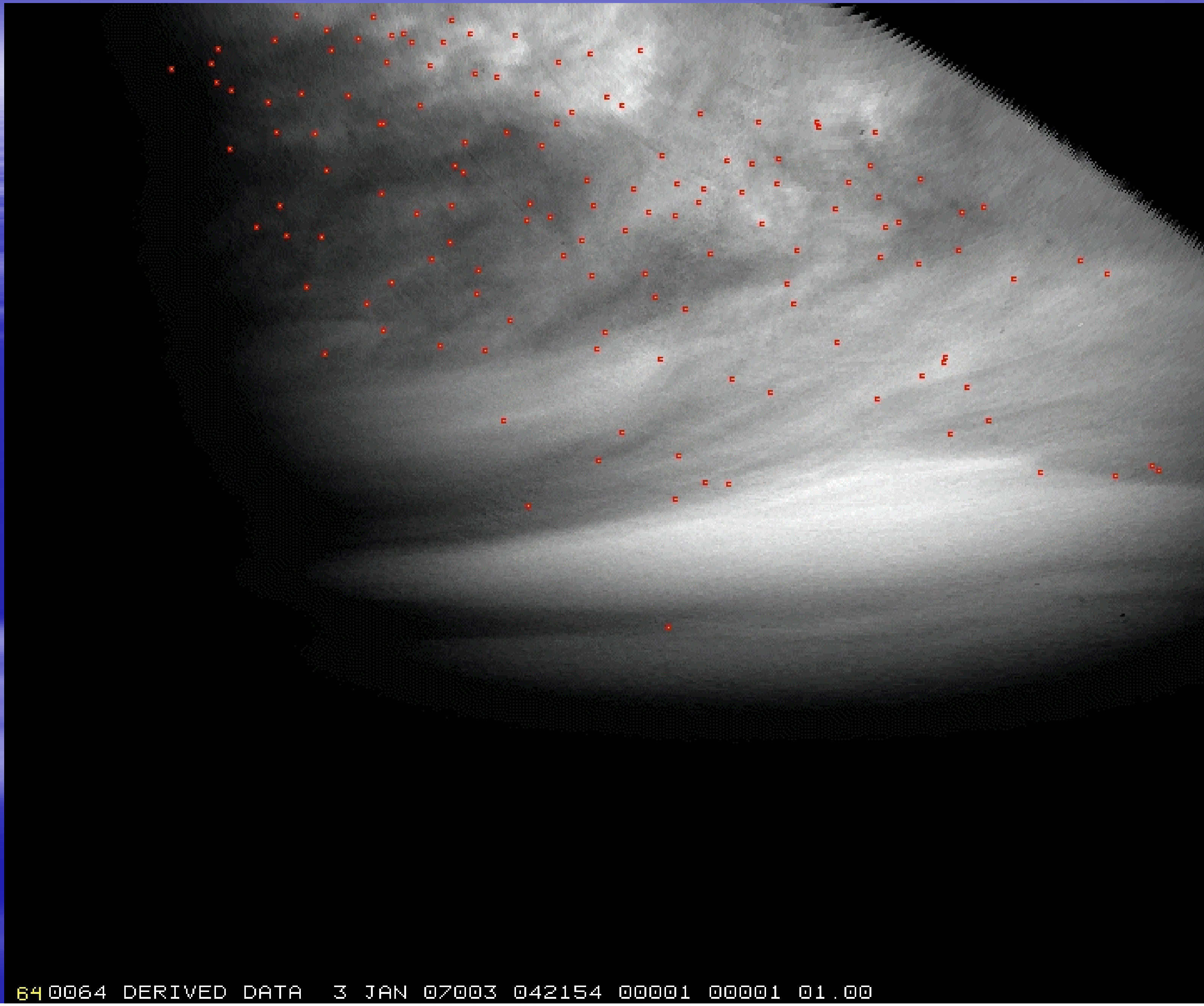
Galileo SSI and NIMS

Venus Clouds

- Sulfuric Acid (75% solution)
- Mostly 1 micron radius droplets (determined first from Polarization data, measured by Pioneer Venus Large Probe) with some larger particles
- Haze in polar latitudes, ~ 0.3 micron radius
- Some larger particles in lower clouds

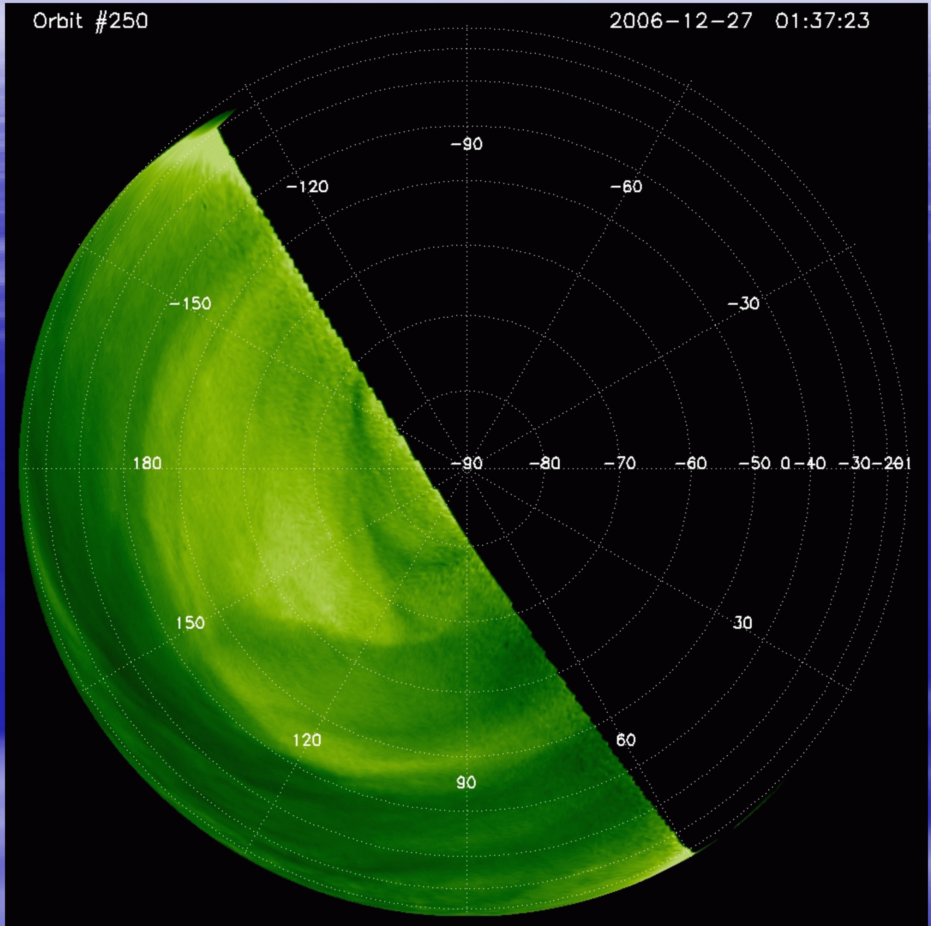


Wind speeds from UV features tracking



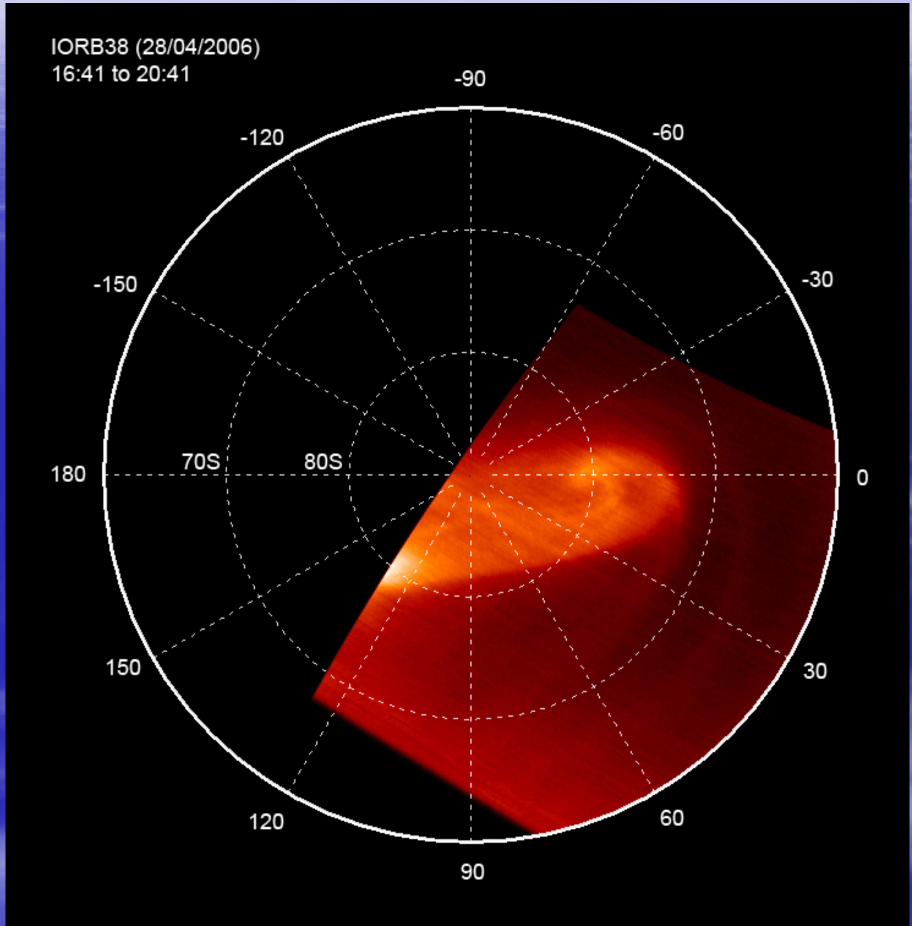
Polar vortex rotation

P ~ 2.8 days

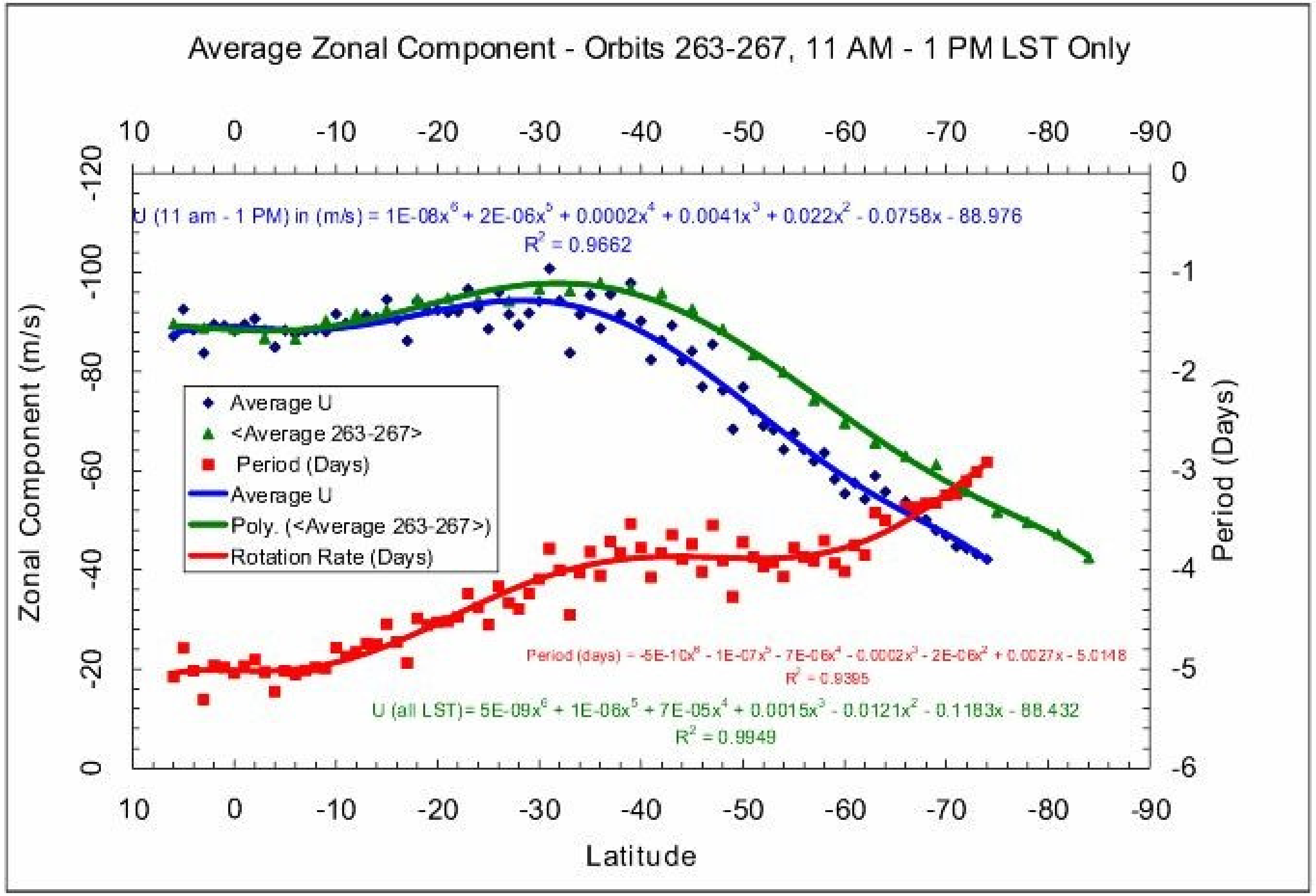


UV / Titov & VMC Team/

P ~ 2.5 days



Thermal IR / Wilson & VIRTIS Team/


Average Zonal Component - Orbits 263-267, 11 AM - 1 PM LST Only
U (11 am - 1 PM) in (m/s) = 1E-08x^6 + 2E-06x^5 + 0.0002x^4 + 0.0041x^3 + 0.022x^2 - 0.0758x - 88.976
R^2 = 0.9662
Average U
<Average 263-267>
Period (Days)
Average U
Poly. (<Average 263-267>)
Rotation Rate (Days)
Period (days) = -5E-10x^6 - 1E-07x^5 - 7E-06x^4 - 0.0002x^3 - 2E-06x^2 + 0.0027x - 5.0148
R^2 = 0.9395
U (all LST)= 5E-09x^6 + 1E-06x^5 + 7E-05x^4 + 0.0015x^3 - 0.0121x^2 - 0.1183x - 88.432
R^2 = 0.9949
Zonal Component (m/s)
Period (Days)
Latitude
10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90
-120 -100 -80 -60 -40 -20 0
0 -1 -2 -3 -4 -5 -6

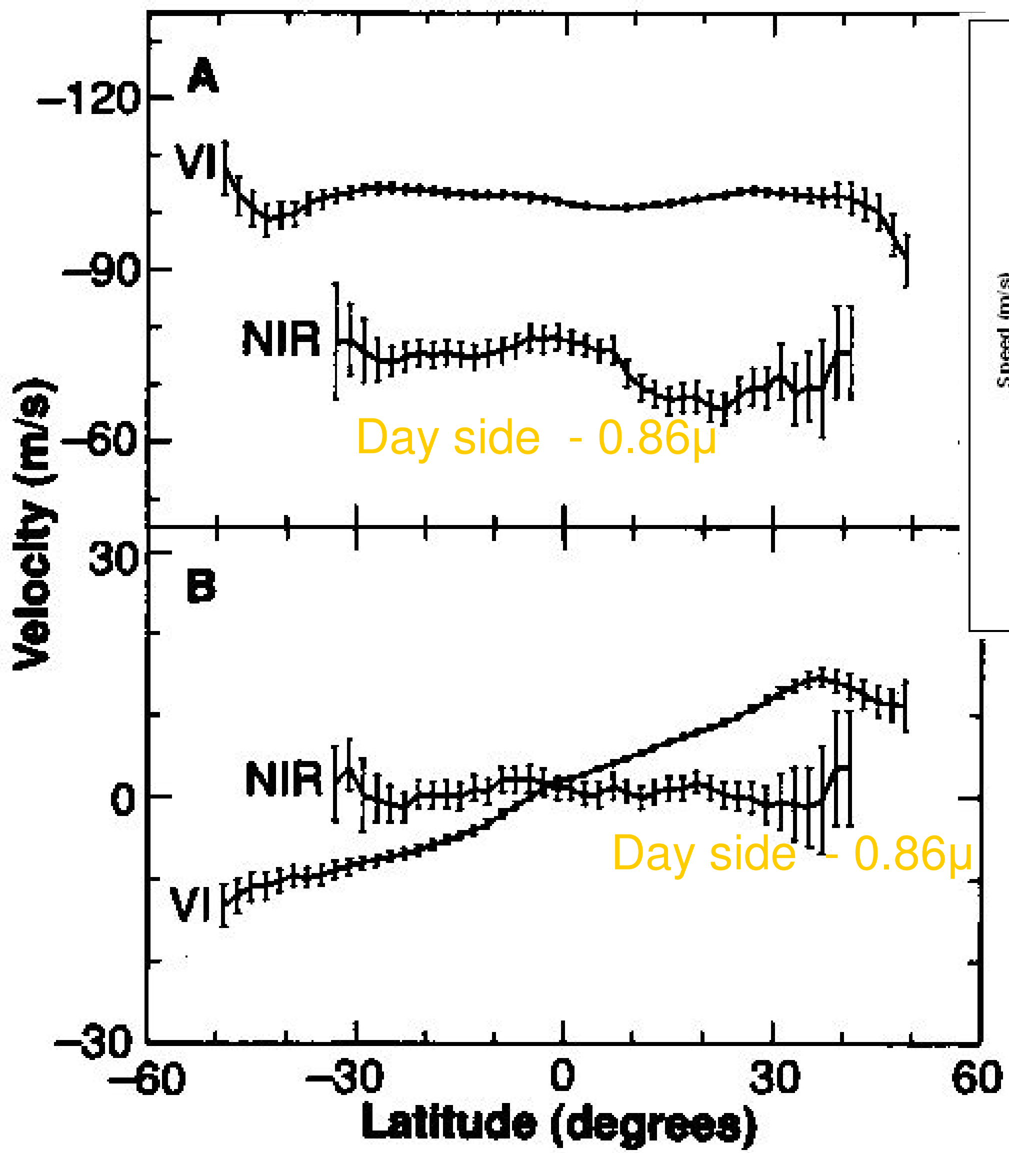
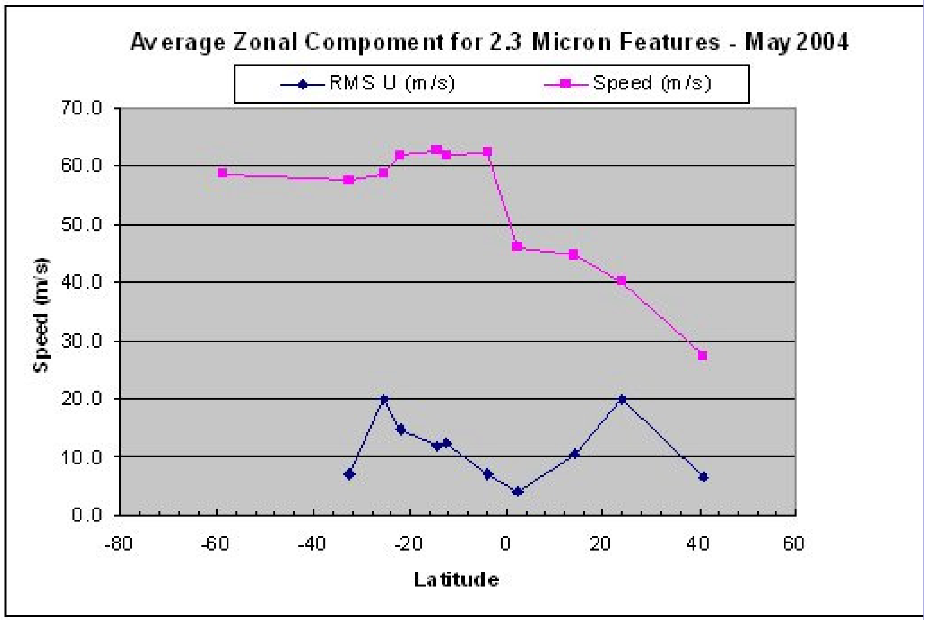


Fig. 5. Velocities of NIR and violet (VI) features as a function of latitude; (**A**) eastward, (**B**) northward. The vertical bars indicate the estimated error, based on the sample standard deviations within each 15° latitude averaging bin.



↑***Ground based 2.3 μ indicating cloud motions at ~ 53 km***

↑***(Limaye et al., 2006, BASI)***

Near Infrared images provide cloud motions at a ~ 55 km level

← ***Galileo SSI (Belton et al., 1991) , ~ 61 km altitude***

Vertical Structure of Zonal Flow from tracking of entry probes

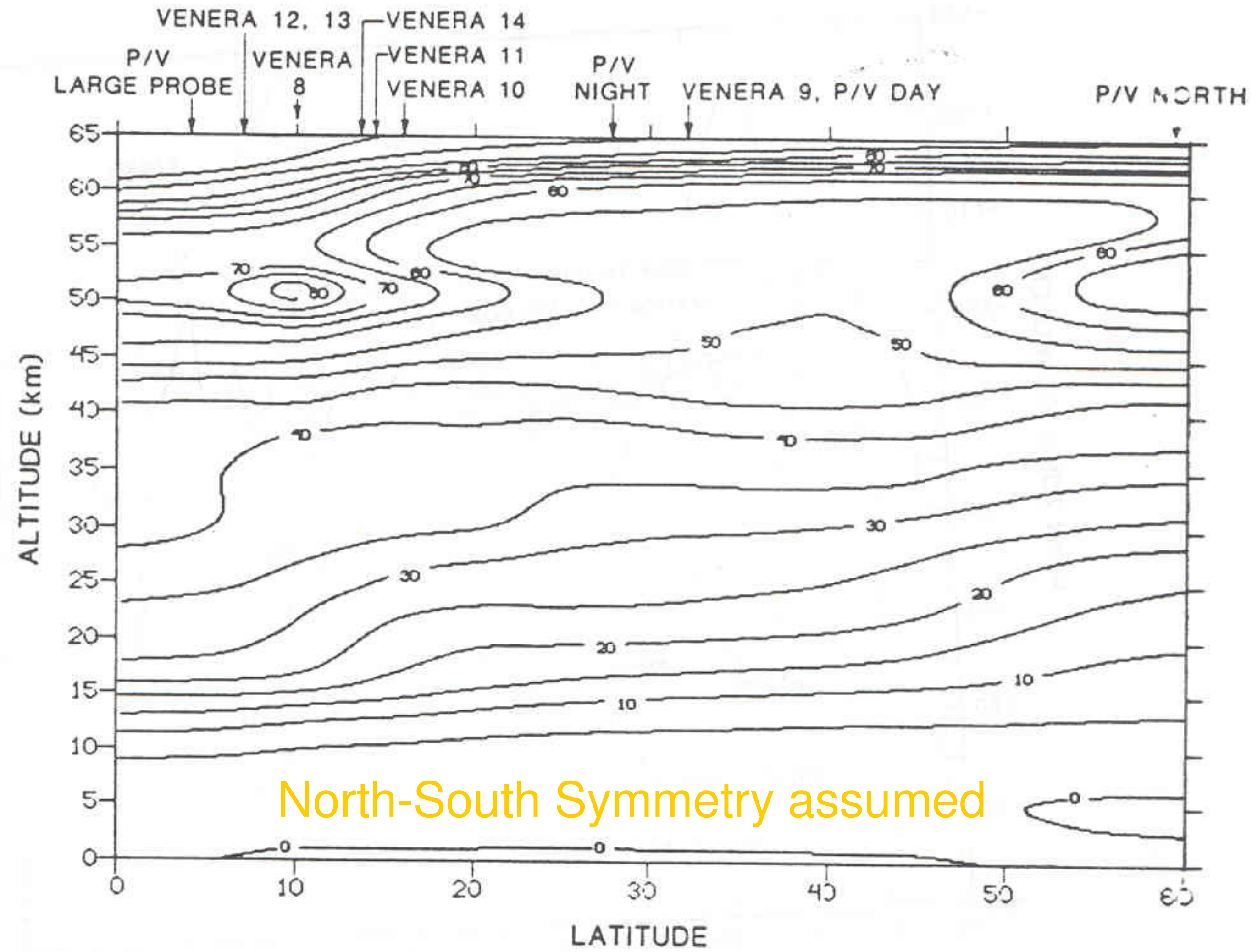
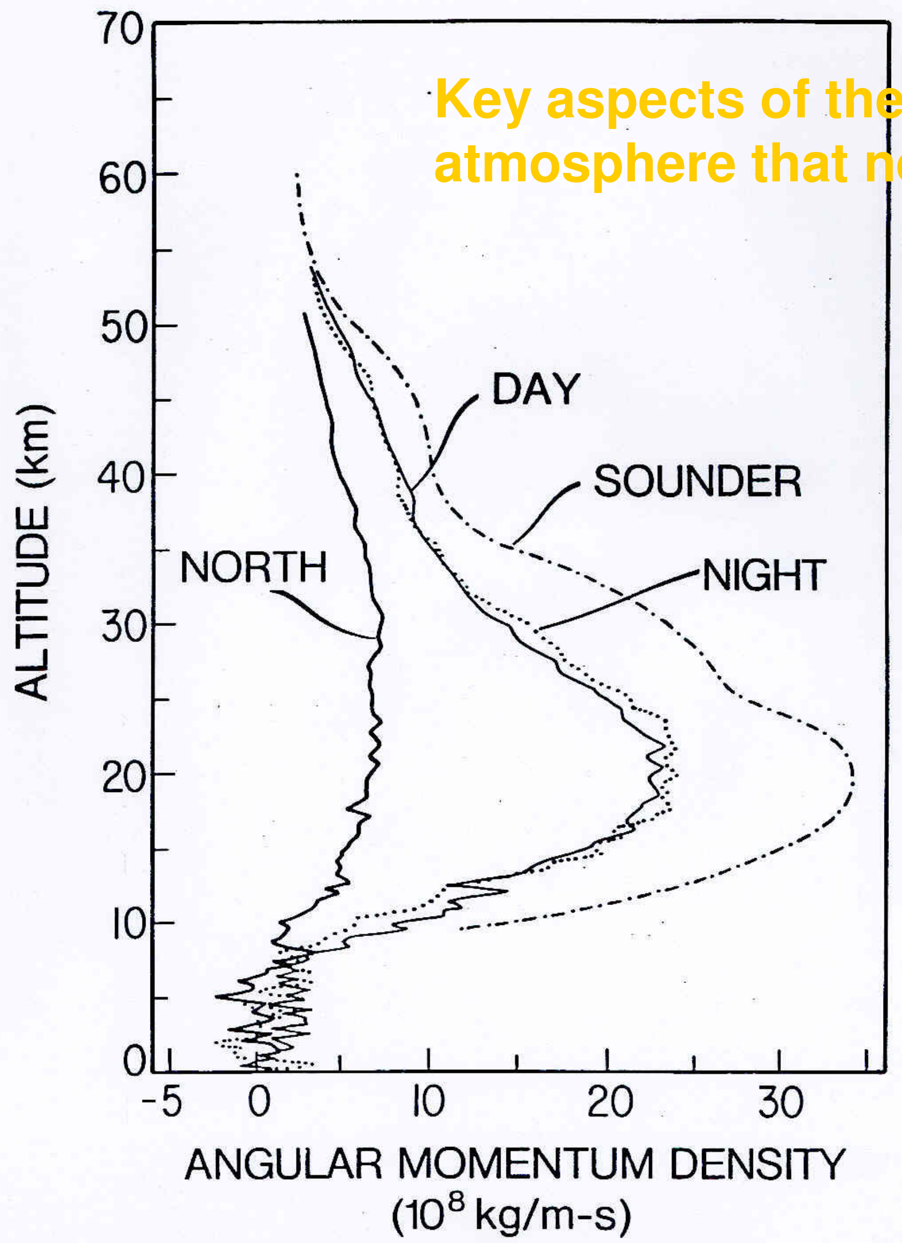


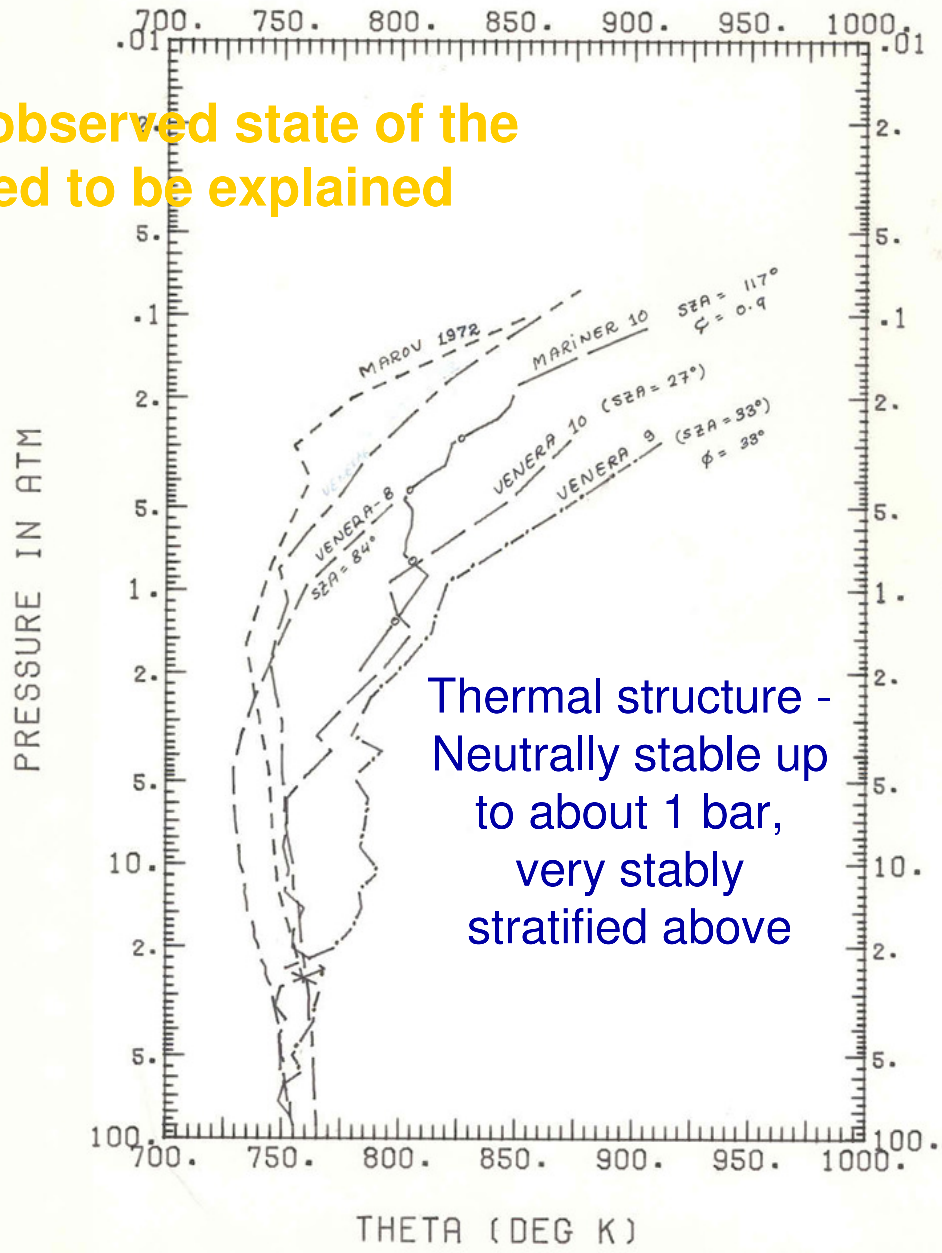
Fig. 1. Meridional cross section of the magnitude of retrograde zonal component of wind (ms^{-1}) constructed from the probe winds by two-dimensional interpolation.

Pioneer Venus Entry Probes

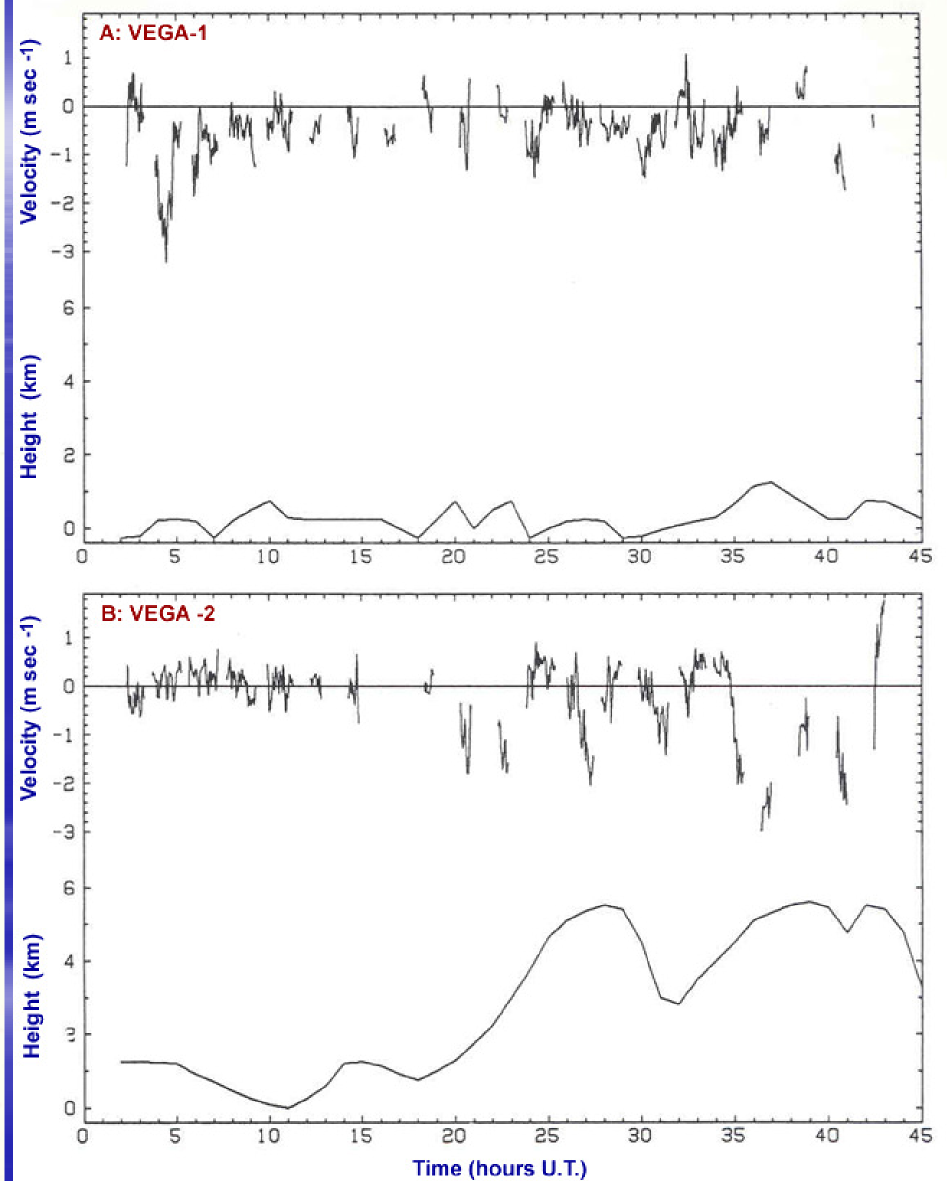
Venera Probe Data

Key aspects of the observed state of the atmosphere that need to be explained



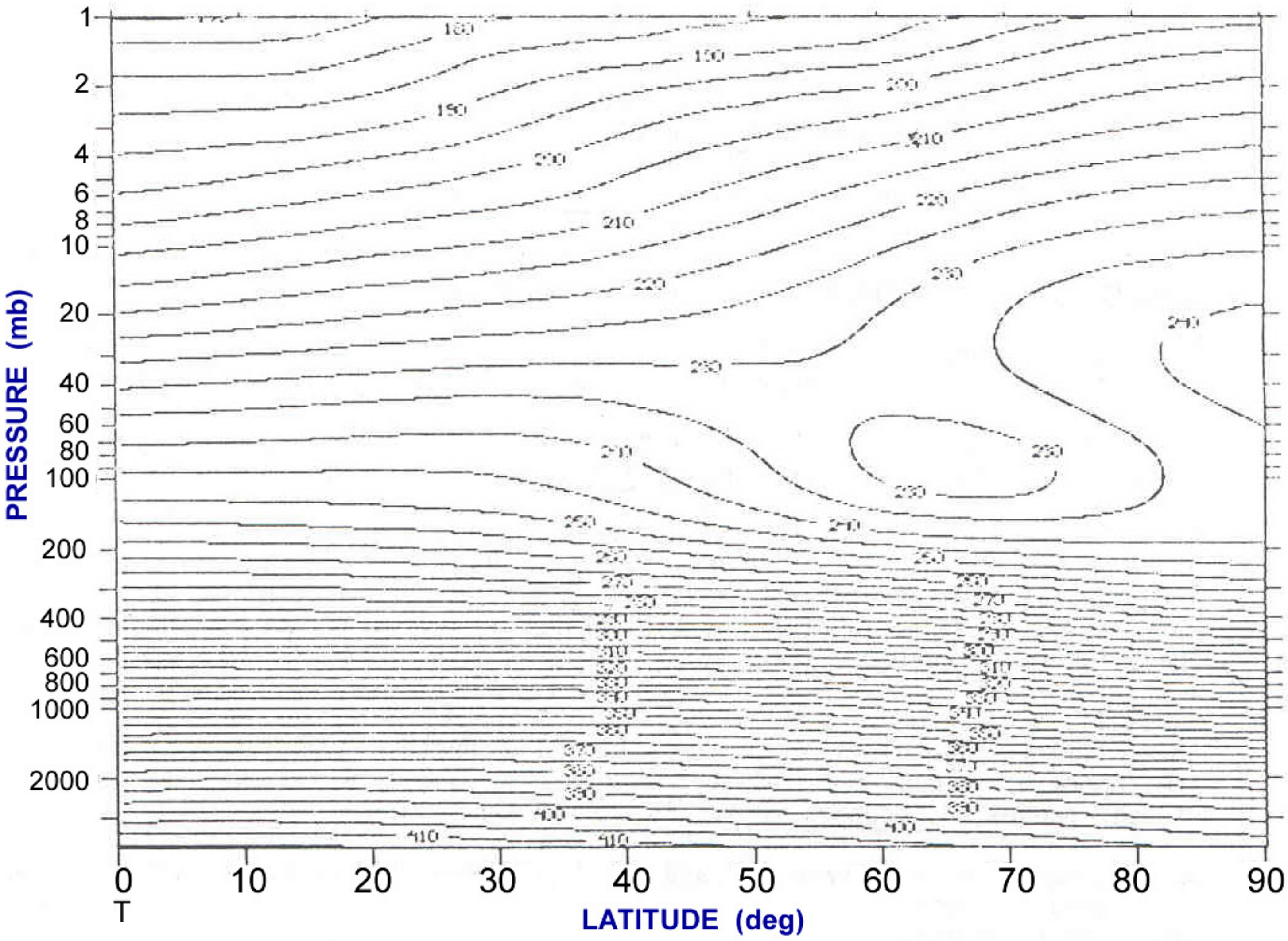


Thermal structure - Neutrally stable up to about 1 bar, very stably stratified above



Comparison of temporal history of atmospheric vertical winds with estimated surface topography. Topography curves, which are referenced to a planetary radius of 6051 km, represent only an envelope of the actual terrain, which may be much more jagged. (A) VEGA-1 (B) VEGA-2

Pioneer Venus Radio Occultations



Contours of temperature data /10/

Cyclostrophically Balanced Flow Computed from Thermal Field inferred directly from Pioneer Venus Radio Occultation Data

Altitude of clouds tracked in average sense can be determined from matching the speed)

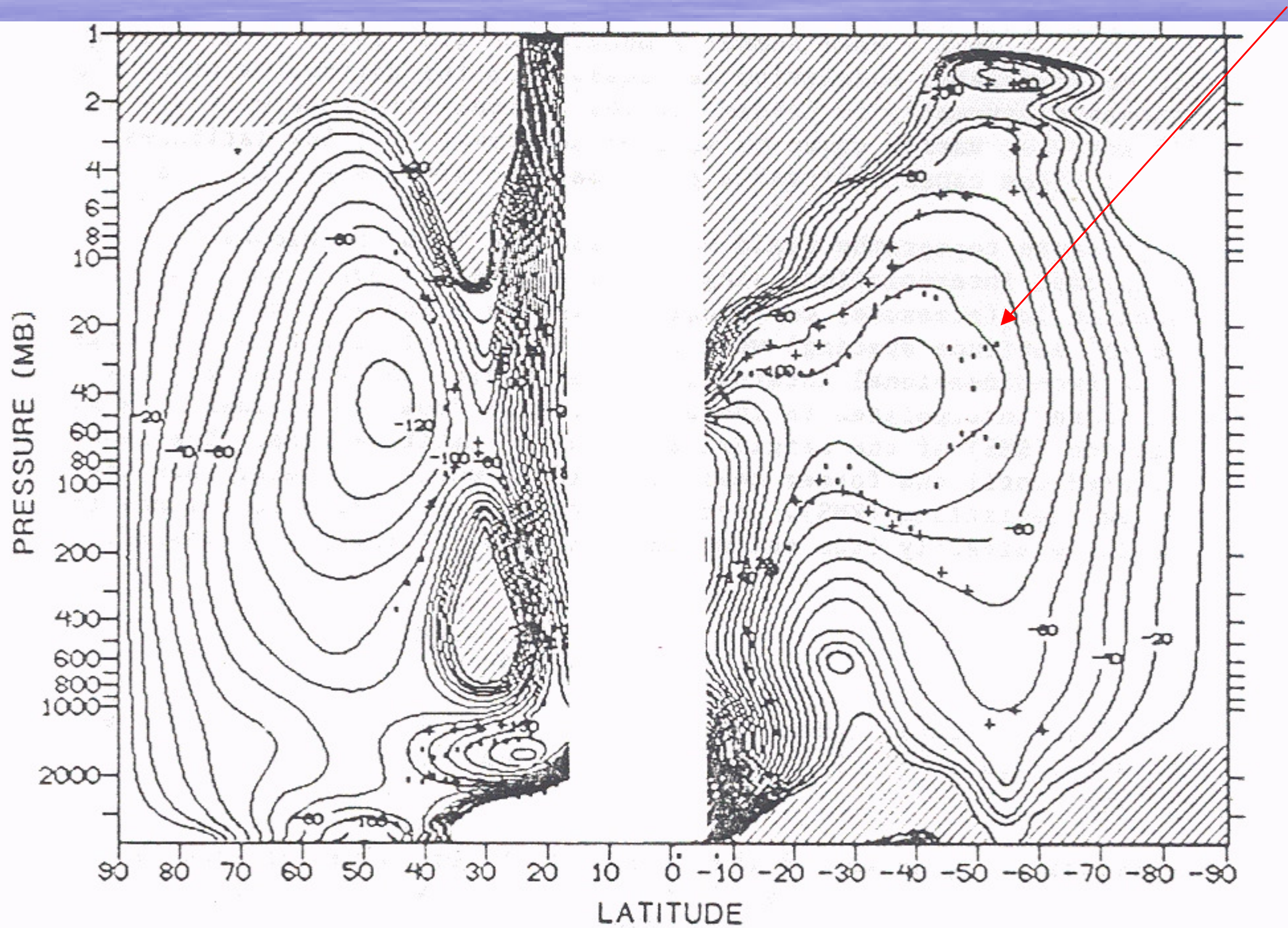
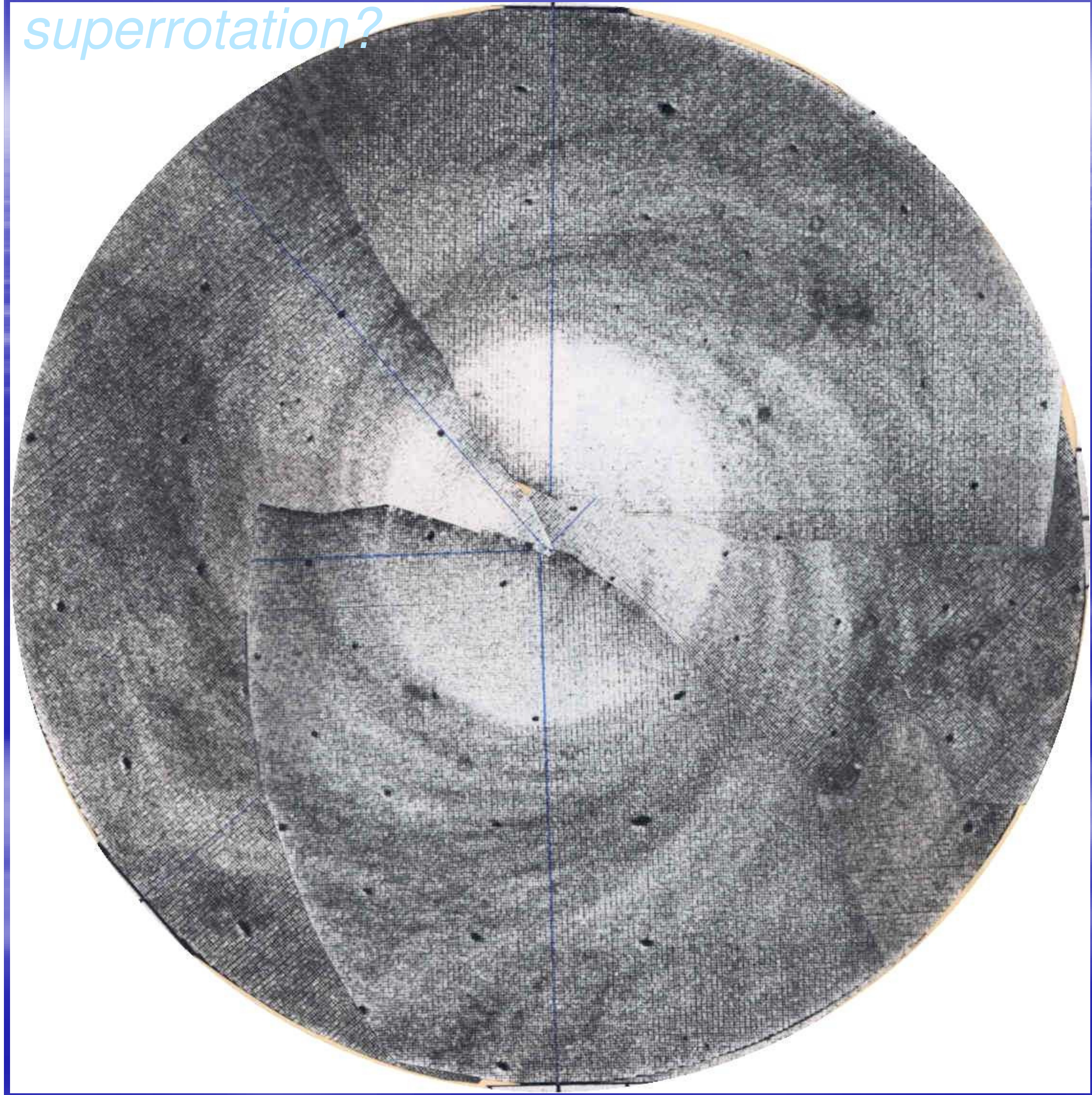


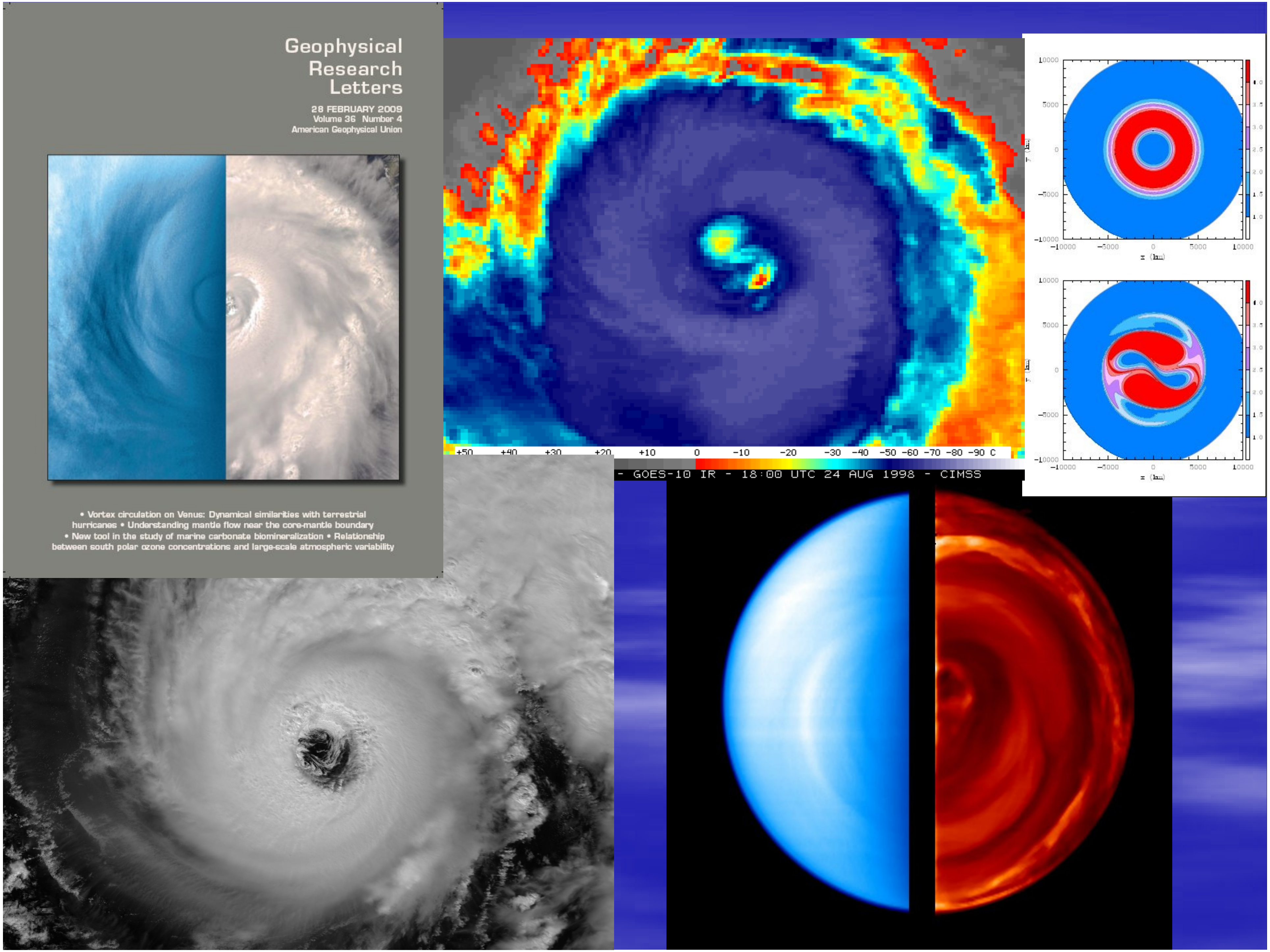
Fig. 5a.

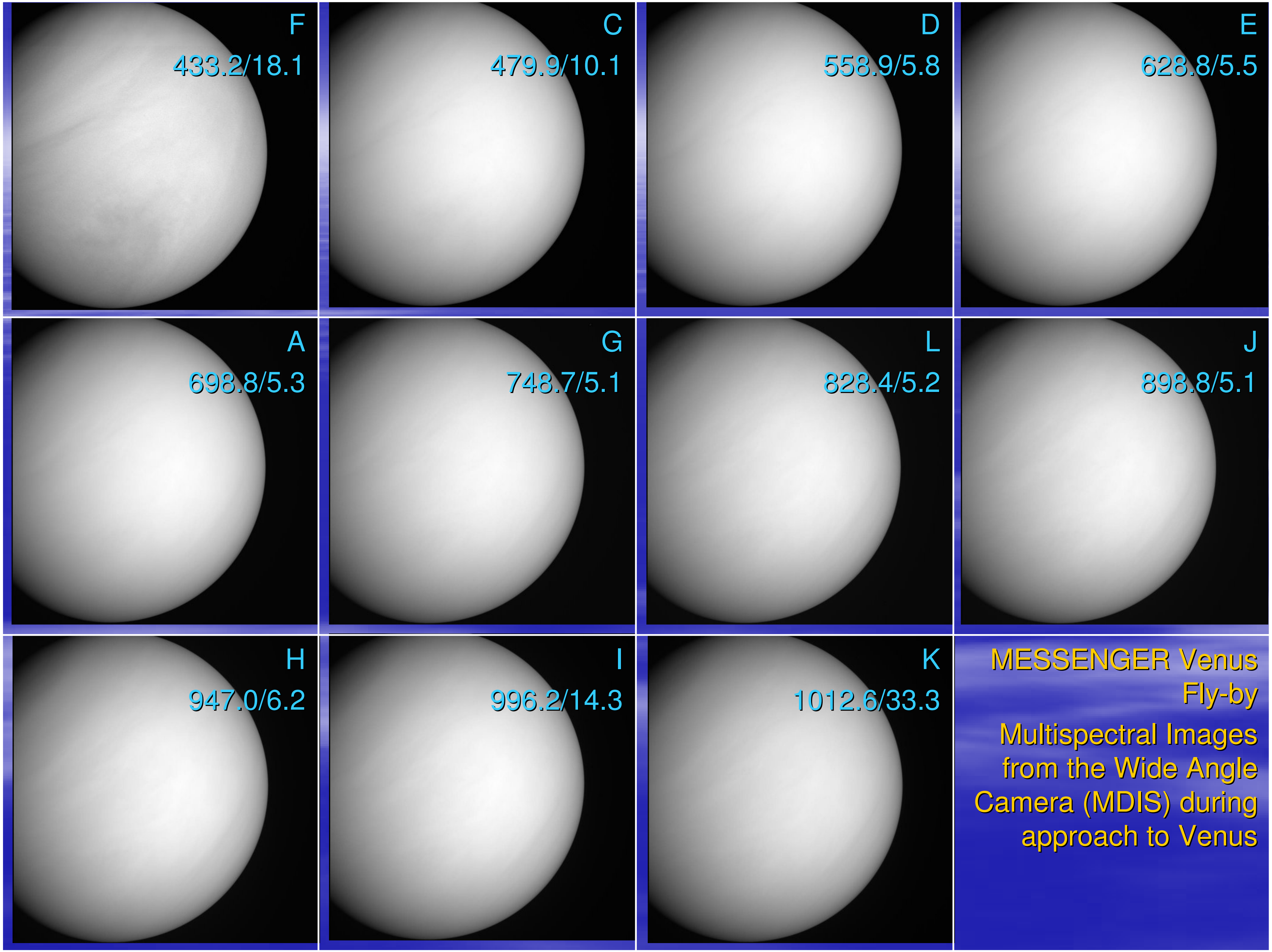
Fig. 5. Zonal component derived from the cyclostrophic balance and the gradient field shown in Figure 4 (ms^{-1}) with pressure as the vertical coordinate (a), and also with height as the vertical coordinate (b). Levels where the observed mean cloud tracked zonal component matches the balanced flow are indicated for Mariner 10 (".") and Pioneer Venus ("+") results.

Vortex Organization of the circulation: Clues to the origin of the superrotation?



Venus atmosphere at the time pf Mariner 10 observations in 1974 was organized in a hemispheric vortex centered over the south pole. A similar vortex existed in the north. Pioneer Venus images also show a similar organization, The mid latitude jet is near the contrast boundary.


Geophysical Research Letters
28 FEBRUARY 2009
Volume 36 Number 4
American Geophysical Union
• Vortex circulation on Venus: Dynamical similarities with terrestrial hurricanes • Understanding mantle flow near the core-mantle boundary • New tool in the study of marine carbonate biomineralization • Relationship between south polar ozone concentrations and large-scale atmospheric variability
+50 +40 +30 +20 +10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90 C
- GOES-10 IR - 18:00 UTC 24 AUG 1998 - CIMSS
10000
5000
0
−5000
−10000
−10000 −5000 0 5000 10000
x (km)


F
433.2/18.1
C
479.9/10.1
D
558.9/5.8
E
628.8/5.5
A
698.8/5.3
G
748.7/5.1
L
828.4/5.2
J
898.8/5.1
H
947.0/6.2
I
996.2/14.3
K
1012.6/33.3
MESSENGER Venus Fly-by
Multispectral Images from the Wide Angle Camera (MDIS) during approach to Venus

What don't we know?

- What causes the superrotation?
- Did it cause the planet to spin backwards?
- What maintains the superrotation?
- How are heat, momentum and trace species transported in the atmosphere? ***Where is the return flow? How is angular momentum supplied to the equatorial region?***
- Is the superrotation a permanent state of the atmosphere?
- What are the UV absorption features?
- How are the NIR features produced?

Understanding the Atmospheric Circulation in an average sense

Needed are:

Large scale zonal and meridional flow profiles with latitude and depth (mean and eddy)

Latitudinal profiles with depth:

- angular momentum transport
- heat transport
- trace species

→ *Need systematic observations (horizontal and vertical over extended periods) and better cloud tracking techniques*

Difficulties in synthesis of data

- Spatial, temporal coverage and resolution very different
- No significant night side observations of circulation available to date – need new NIR global observations
- Vertical coverage of measurements is poor except for a few entry probes at different times
- Longer period observations biased in solar phase angle (particularly from highly elliptic orbits)
- Meridional flow has not been well measured

What still need to observe and model

- Angular Momentum Balance
- Transport of Heat
- Transport of Trace Species
- Role of thermal tides and gravity/planetary scale waves
- Surface/Atmosphere Interaction

Experience of Cloud Tracking on Venus

- Visual (single point tracking) and Cross-correlation used in both side-by-side (pairs) and time lapse display (triplets or multiples)
- Automated cross-correlation method requires much manual effort for quality control:
  - Vector pair consistency
  - Frequency distribution in latitude bands

Summary

Compared to Earth, for a very slowly rotating planet with nearly uniform cloud cover, thick atmosphere, no seasons, no land-ocean differences with no significant hydrologic cycle, no significant topography, the planet exhibits an elegant vortex circulation with super rotating winds.

Why? How?

Thank you!

You are invited to attend:

Venus Exploration Analysis Group (NASA) 8th Meeting and Workshop, “Venus Atmosphere from Surface to Thermosphere” in Madison, Wisconsin, 30 August – 2 September 2010.

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