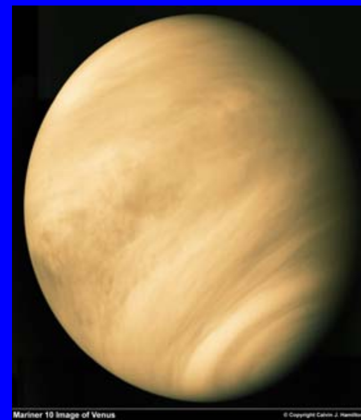

Venus: Atmospheric Circulation

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Space Science and Engineering Center

University of Wisconsin-Madison

Chapman Conference

13-17 February 2006, Key Largo, Florida

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

Venus Atmospheric Circulation: Observations

- First reported by Boyer and Guerin from UV 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) and Balloons (Vega 1 and Vega 2)
- Tracking features in images/maps from spacecraft (UV, Near IR)
- Indirect inferences from thermal structure
- Surface wind from anemometers on Venera probes
- Indirect inferences from wind produced patterns on the Venus surface (Magellan radar imagery)

What do we know?

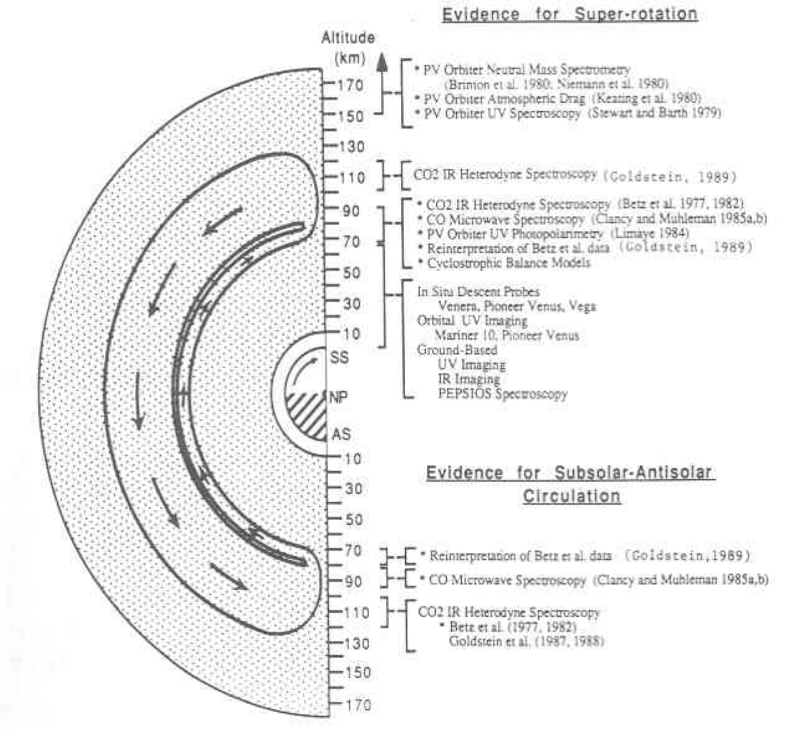


Figure 6. Dynamical regions of Venus' mesosphere and thermosphere (figure from Goldstein 1989).

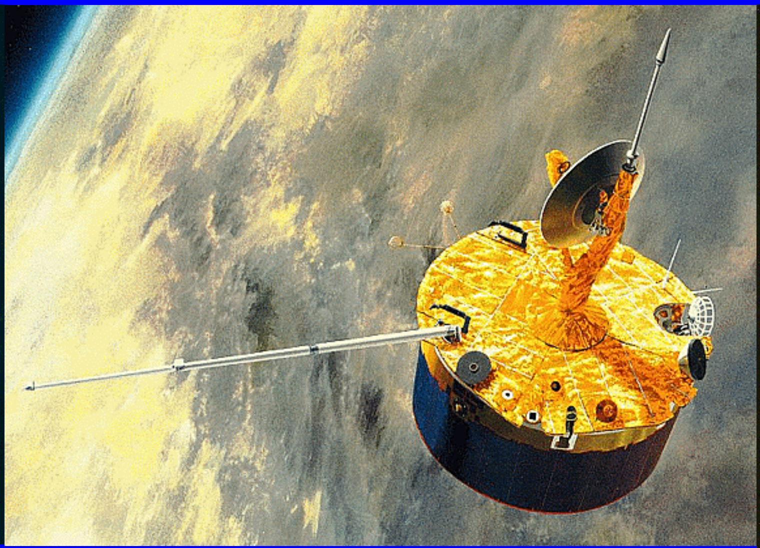
- Bulk of the atmosphere (below ~ 95 km) rotates faster in the same direction as the solid planet with a weak poleward flow at all observed levels.
- strength is variable ~ months.
- circulation organized into two hemispheric vortices centered over each pole with mid latitude jets near 45° latitude, 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?*

Horizontal Structure of the Circulation

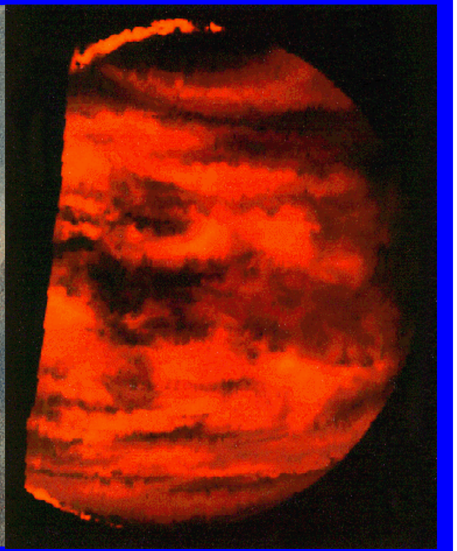
Feature Tracking in Spacecraft Images

- 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 and Near IR imaging (~ 10 hours)

Mariner 10 Television Images



Pioneer Venus OCPP



Galileo SSI and NIMS

Vertical Structure of Zonal Flow from tracking of entry probes

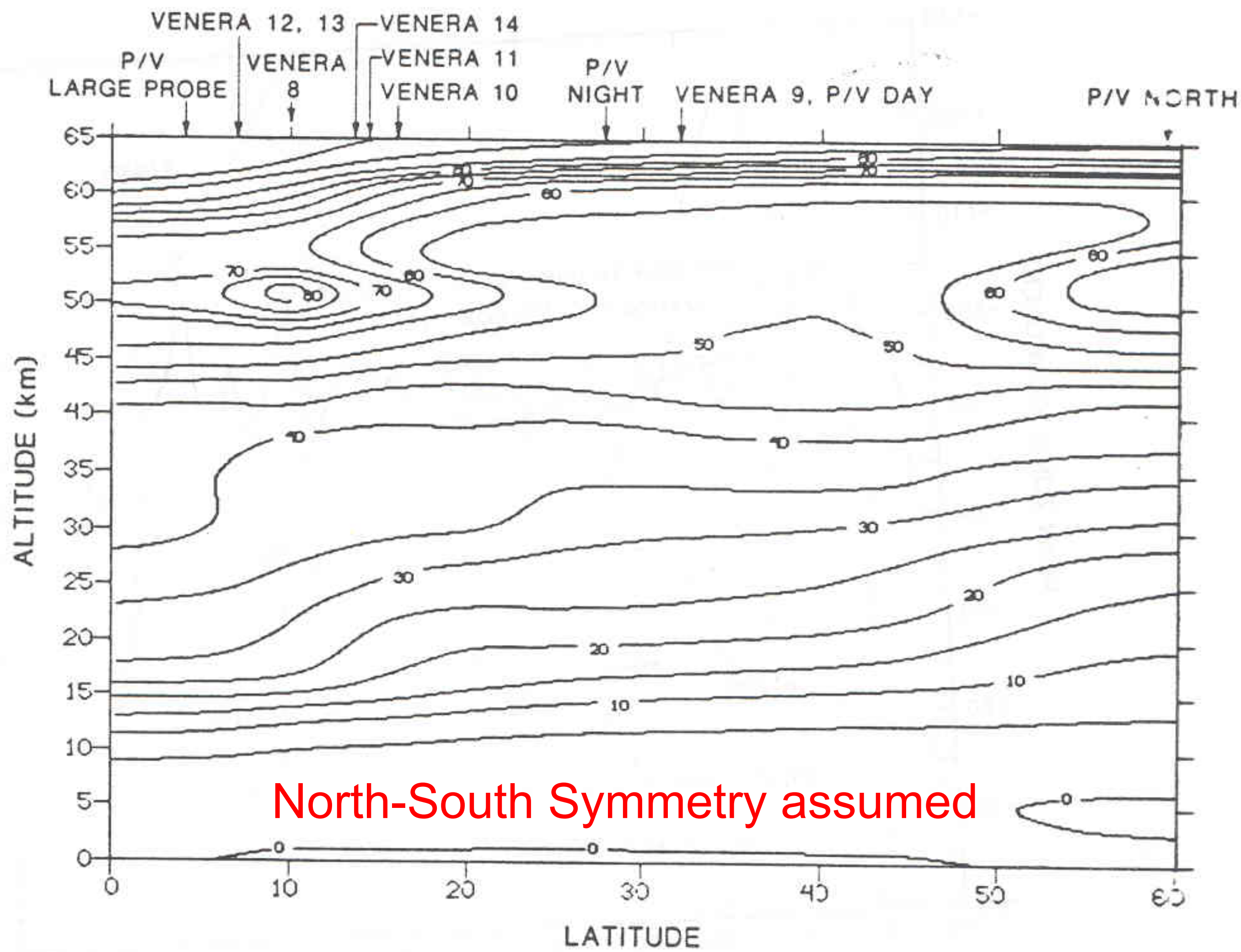
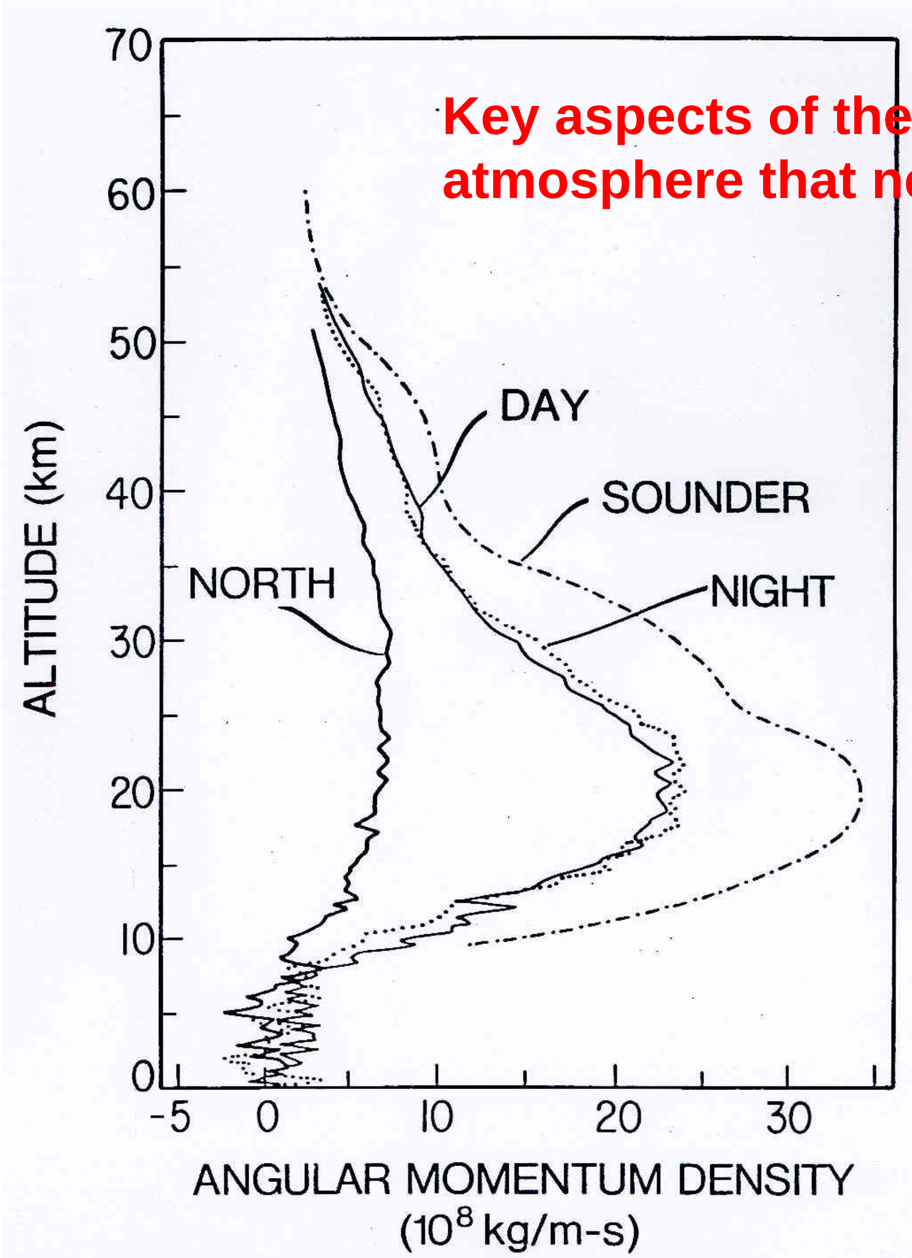


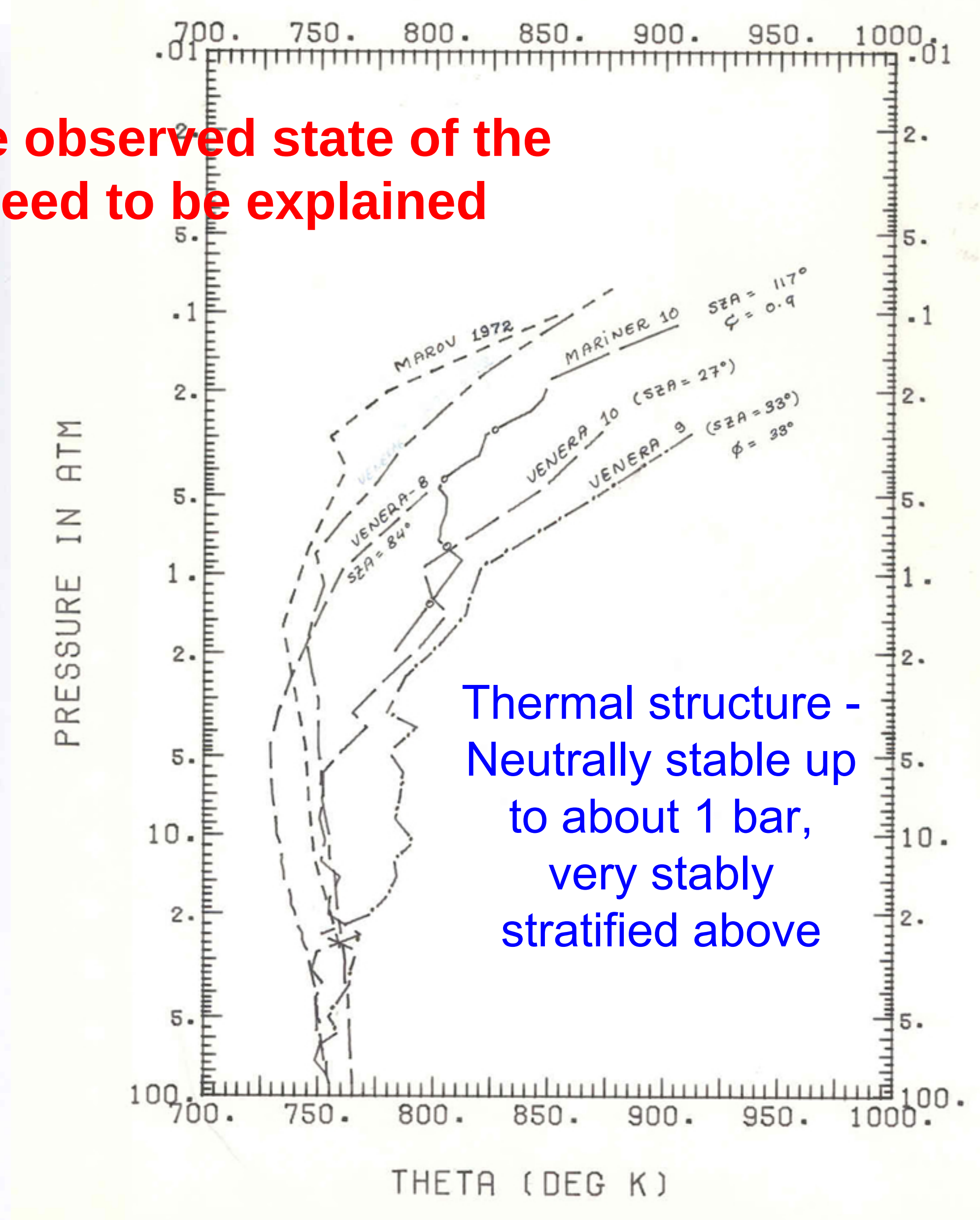
Fig. 1. Meridional cross section of the magnitude of retrograde zonal component of wind (ms^{-1}) constructed from the probe winds by two-dimensional interpolation.

Pioneer Venus Entry Probes

Venera Probe Data

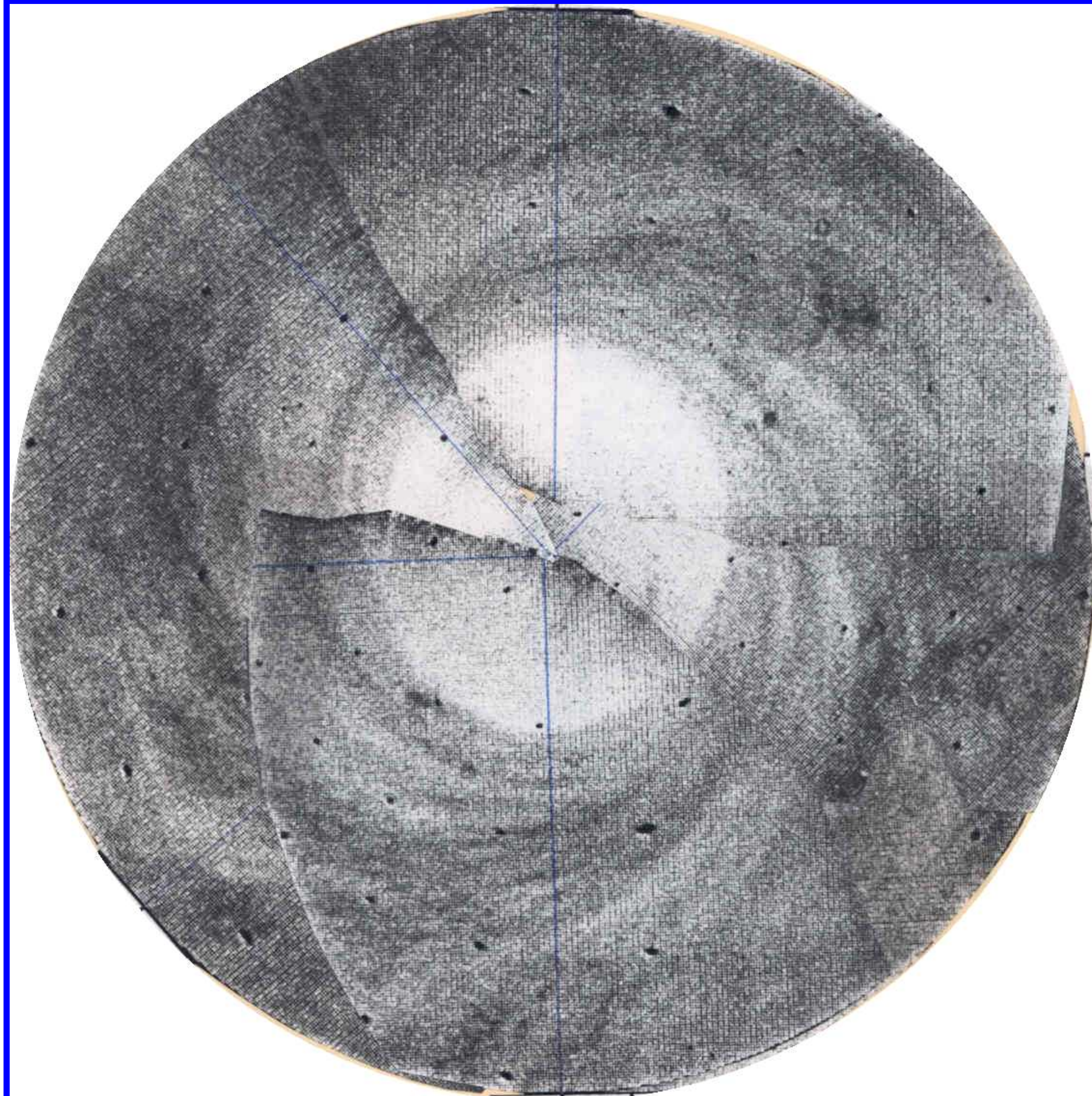
Key aspects of the observed state of the atmosphere that need to be explained



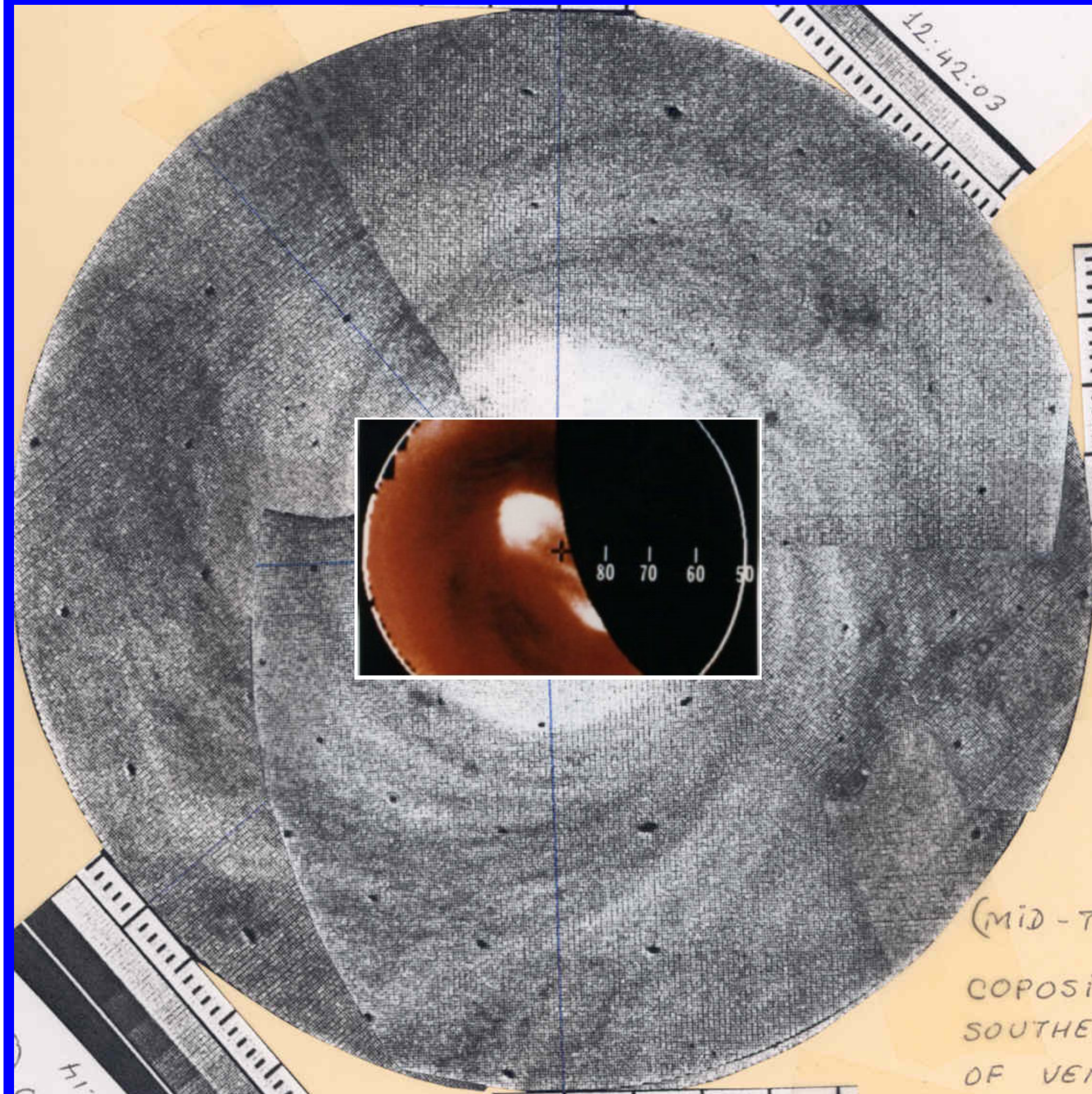


Thermal structure - Neutrally stable up to about 1 bar, very stably stratified above

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.



Vortex Organization of the Venus Atmosphere from Mariner 10 (1974, left) and Pioneer Venus Images (1980, below) with the IR Dipole feature superposed

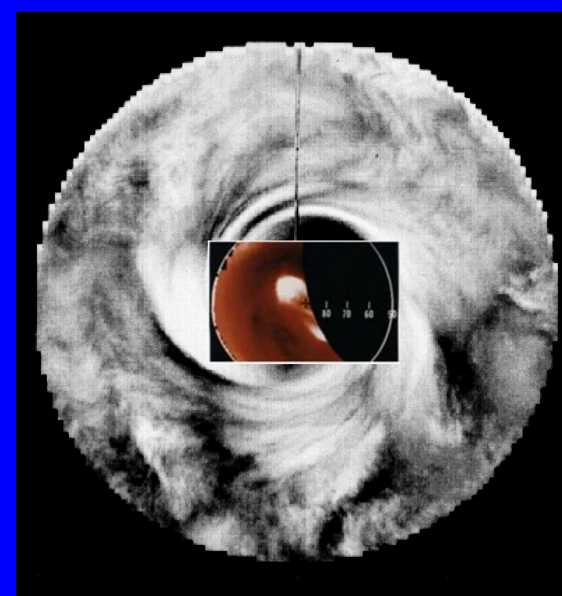
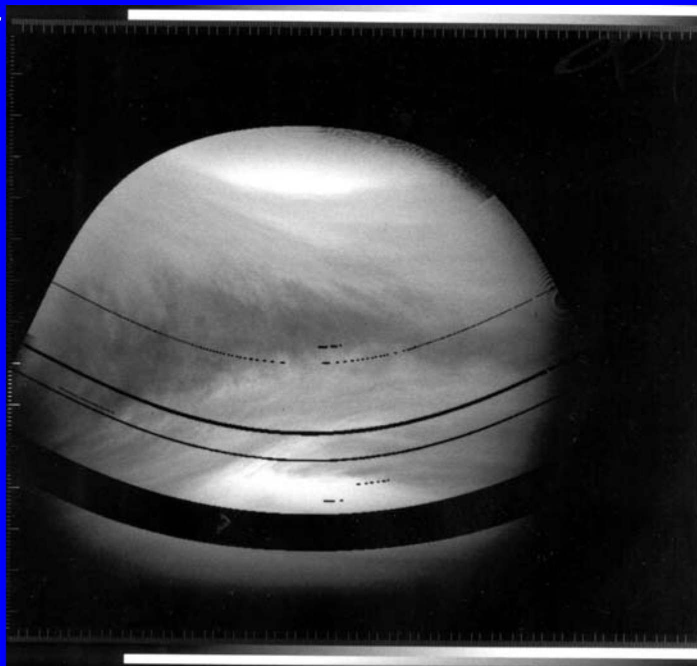
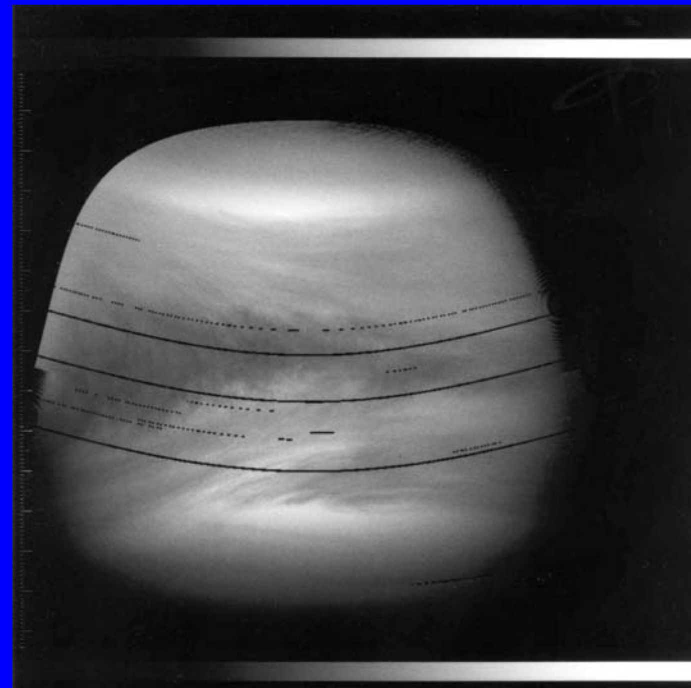
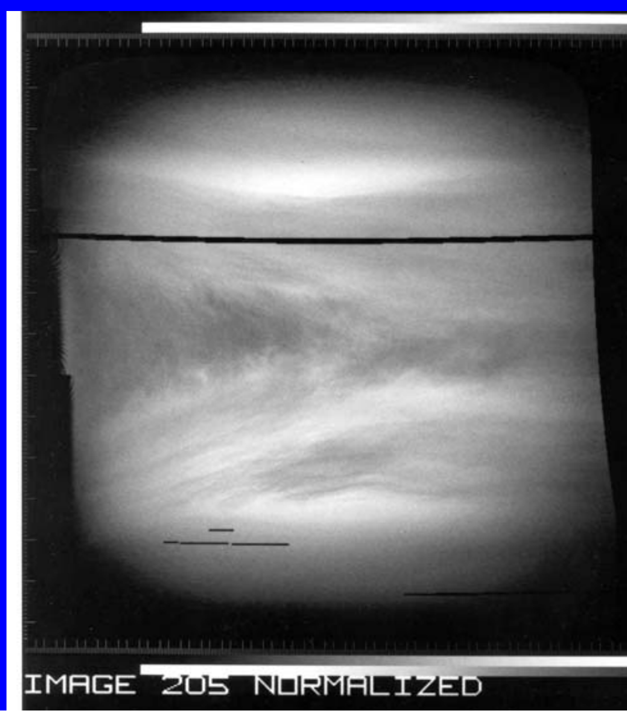


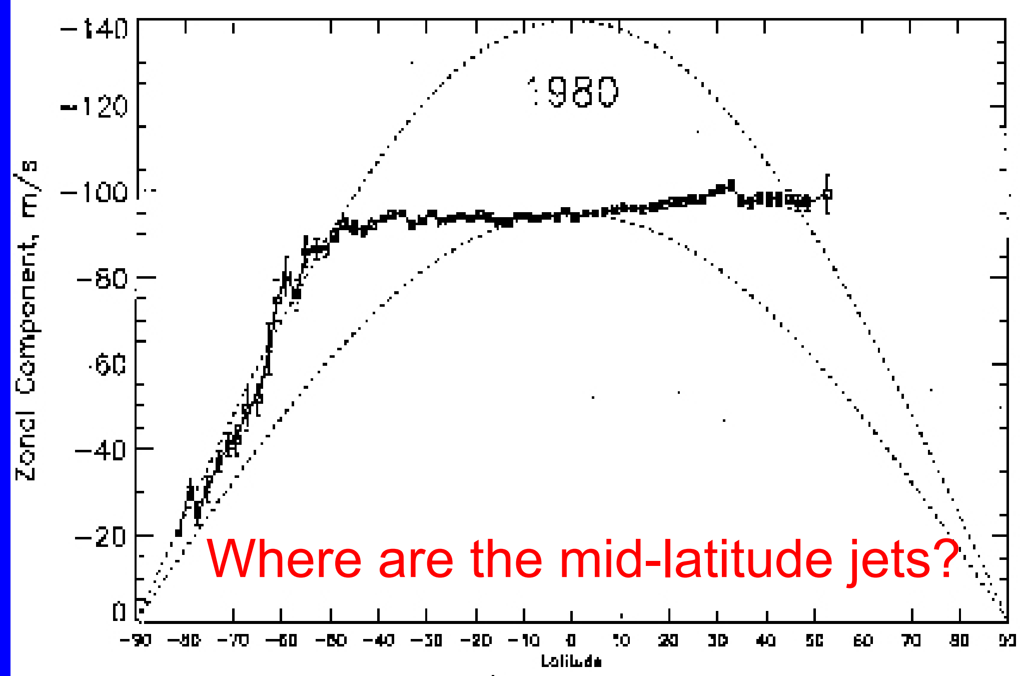
Illustration of Cloud Feature Tracking:

Pioneer Venus OCPP images (365 nm)

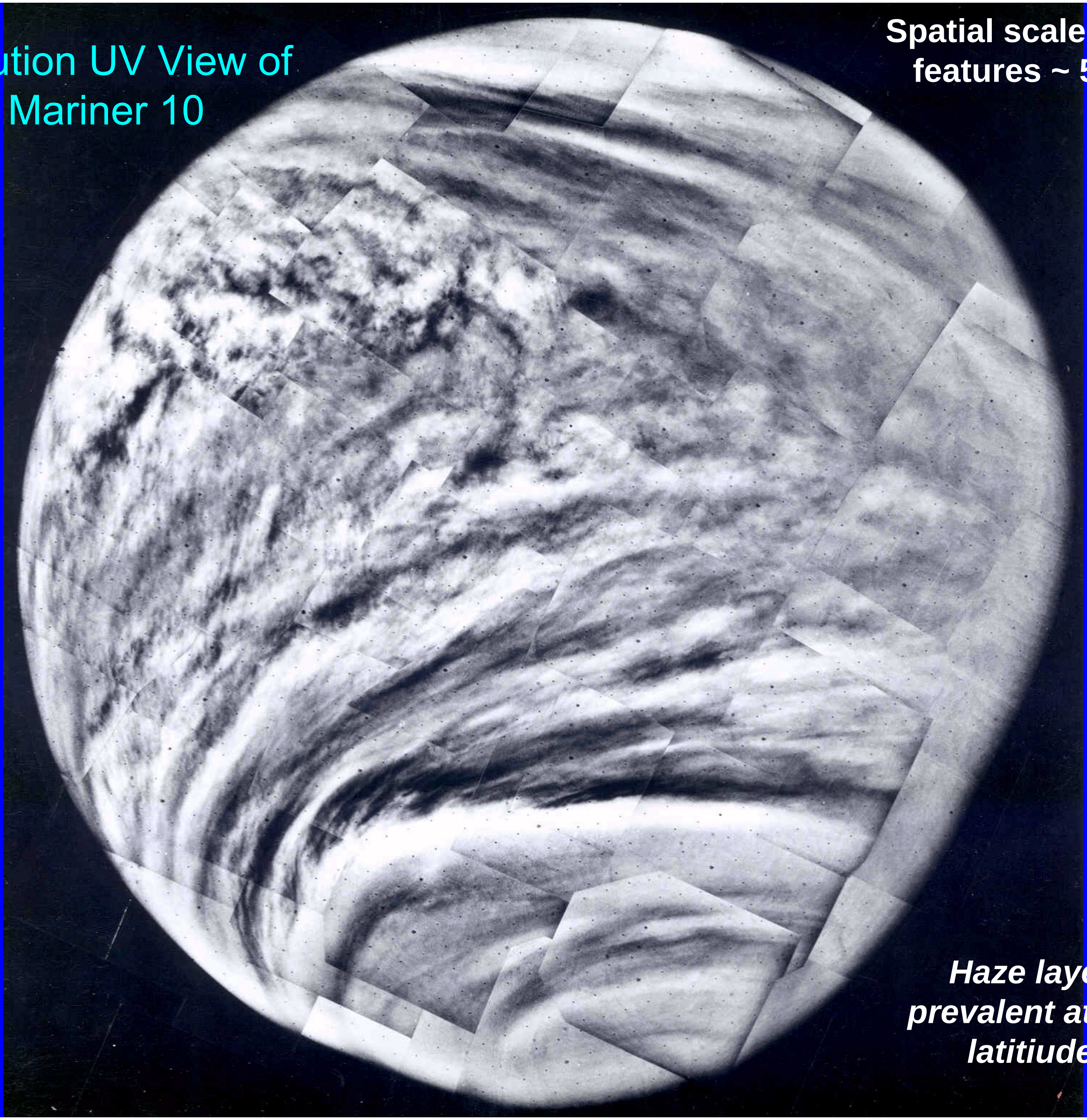








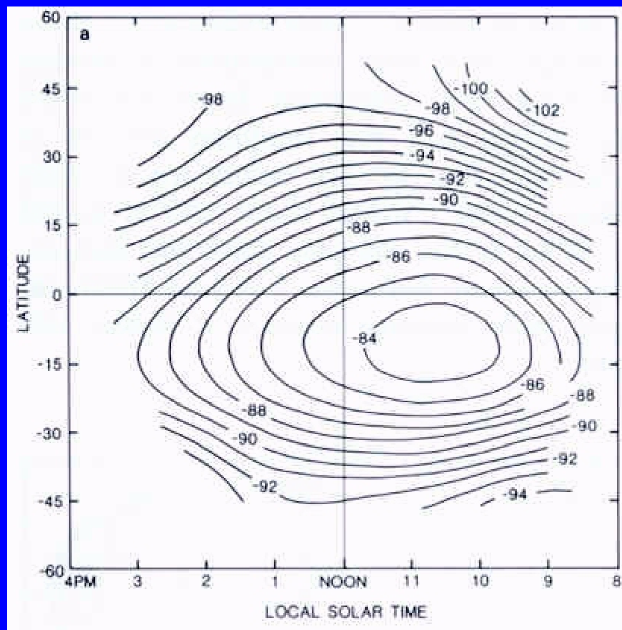
High Resolution UV View of Venus from Mariner 10



Spatial scale of UV features ~ 5 km

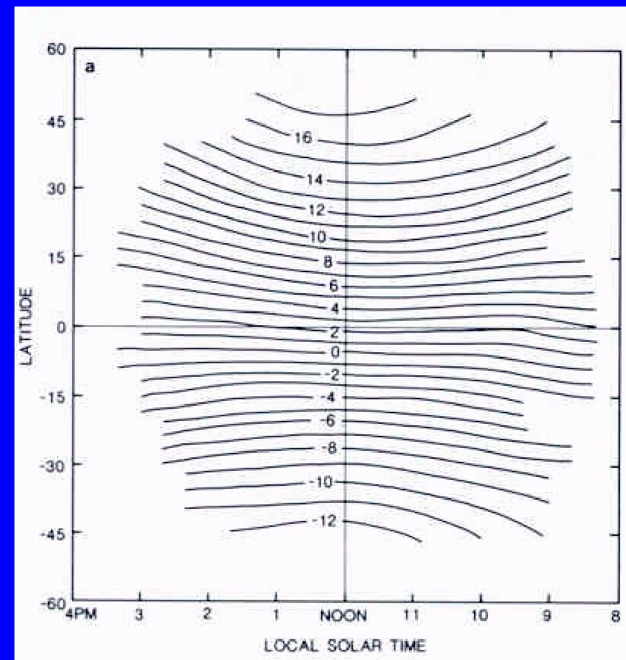
Haze layers prevalent at high latitiudes

Solar Longitude Dependent Circulation



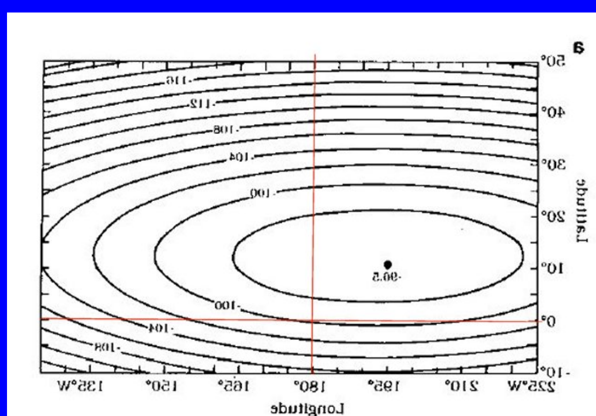
Pioneeer Venus OCPP

Limaye et al. (1982)



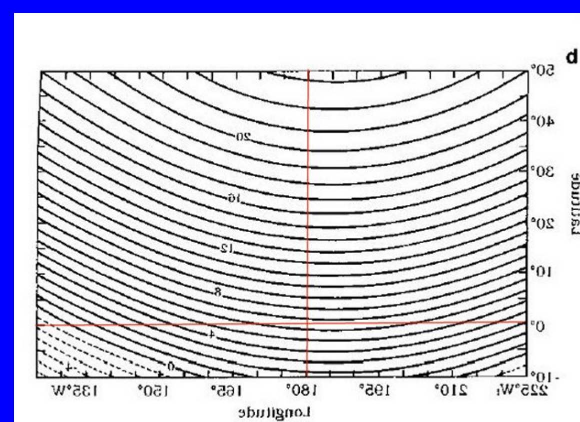
Zonal component

Meridional component

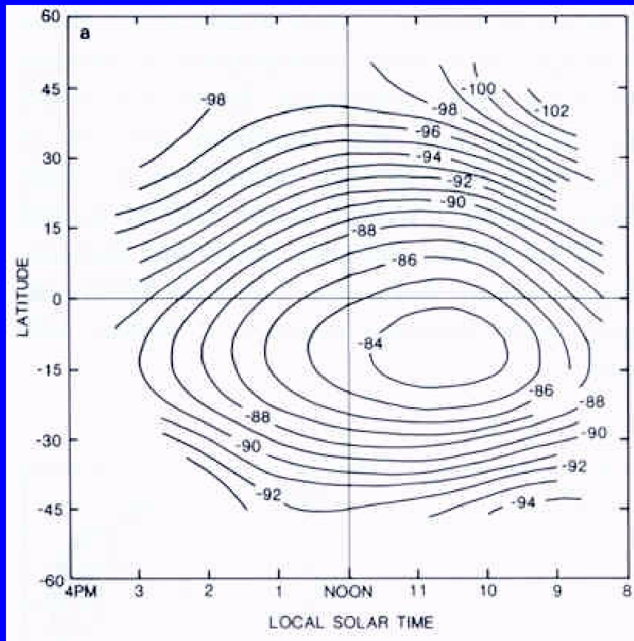


Galileo SSI

Toigo et al.

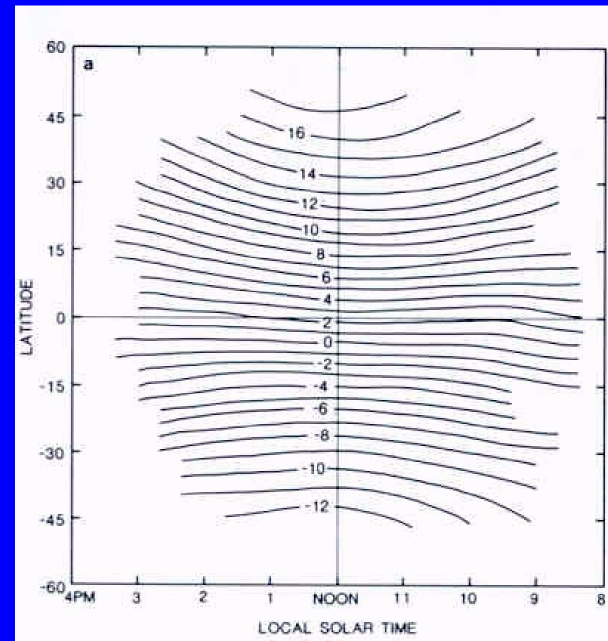


Solar Longitude Dependence of Zonal Flow

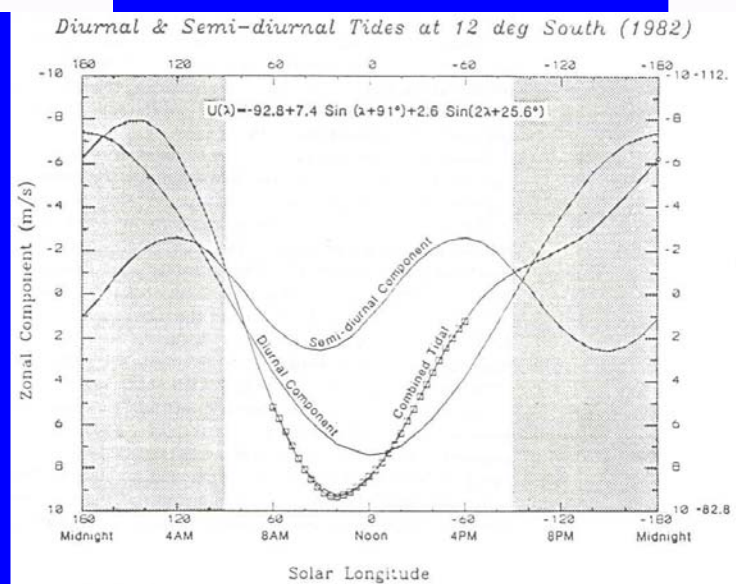


Evidence of Solar Thermal tides

Flow not perfectly symmetric across equator



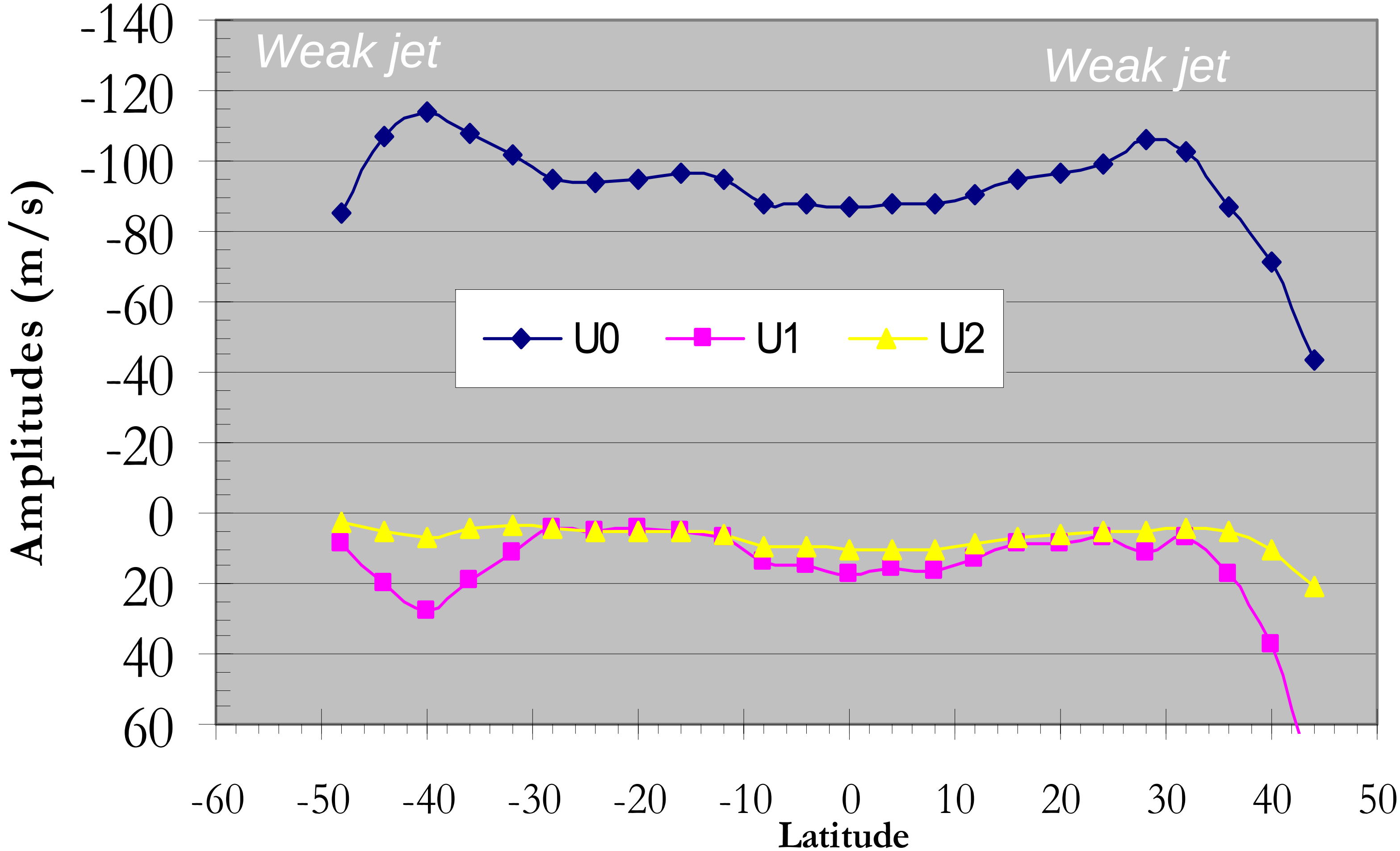
Fit to the day-side winds with diurnal and semidiurnal component mode



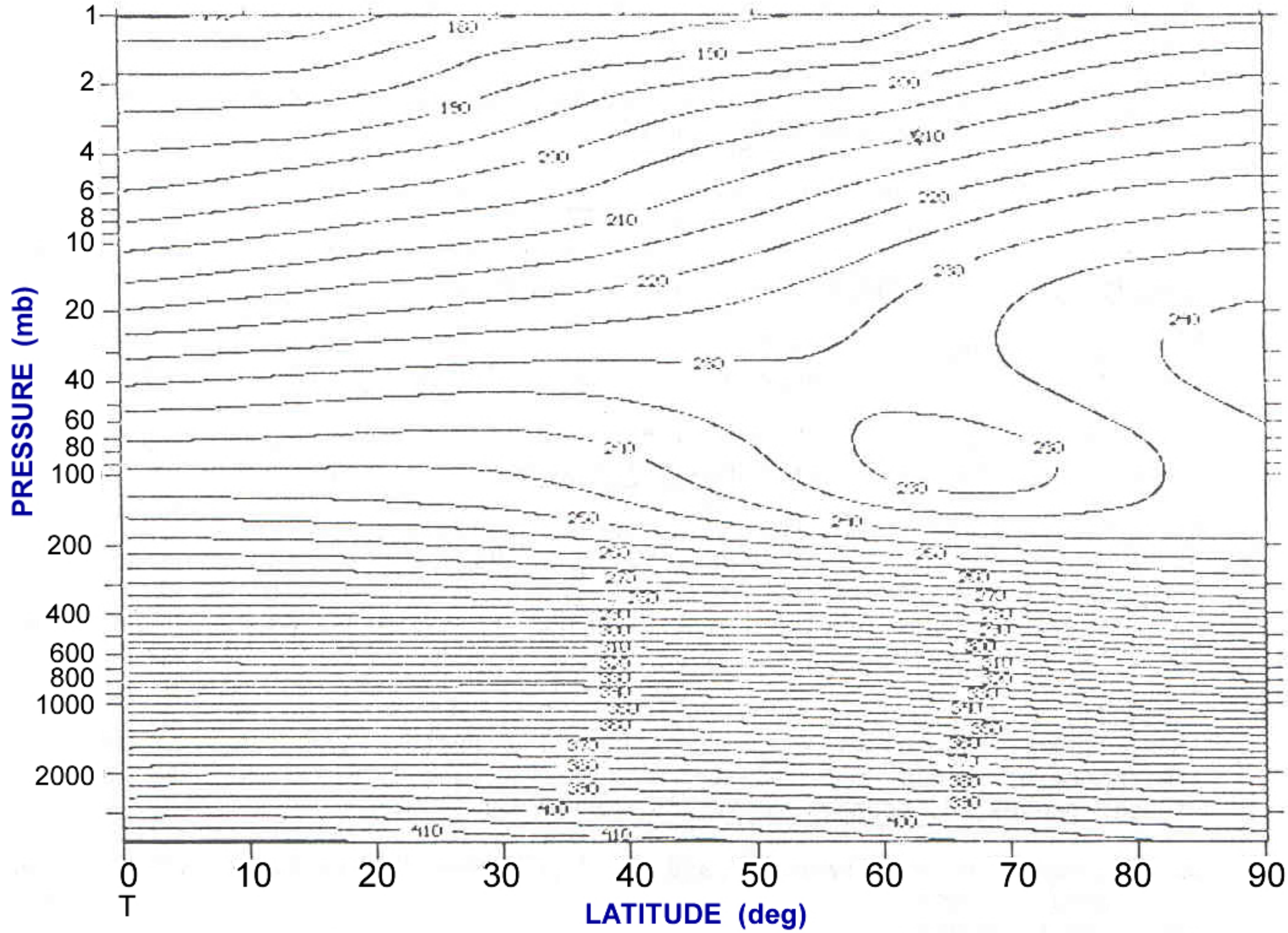
Peak zonal component at ~ 4 AM. Consistent with entry probes – Venera 8 (~ 10 deg lat) shows the fastest wind

Thermal Tides - Zonal Component Amplitudes (1980)

$$U(\lambda) = U_0 + U_1 \, Sin(\Phi_1 + \lambda) + U2 \, Sin(\Phi_2 + 2\lambda)$$



Pioneer Venus Radio Occultations



Contours of temperature data /10/

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

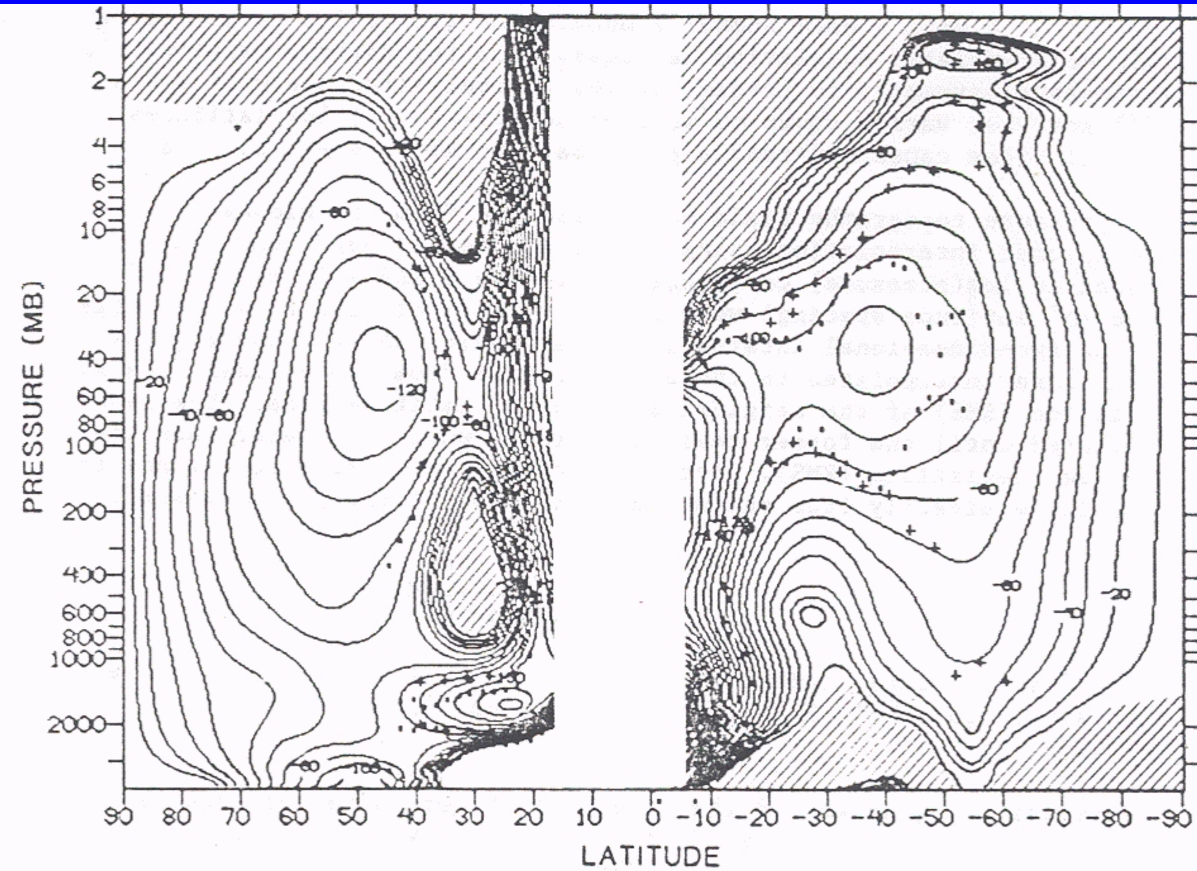


Fig. 5a.

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.

Thermally Direct (Solenoidal) Circulation deduced from Pioneer Venus Radio Occultation Data (Limaye, 1983 *Adv. Sp. Res.)*

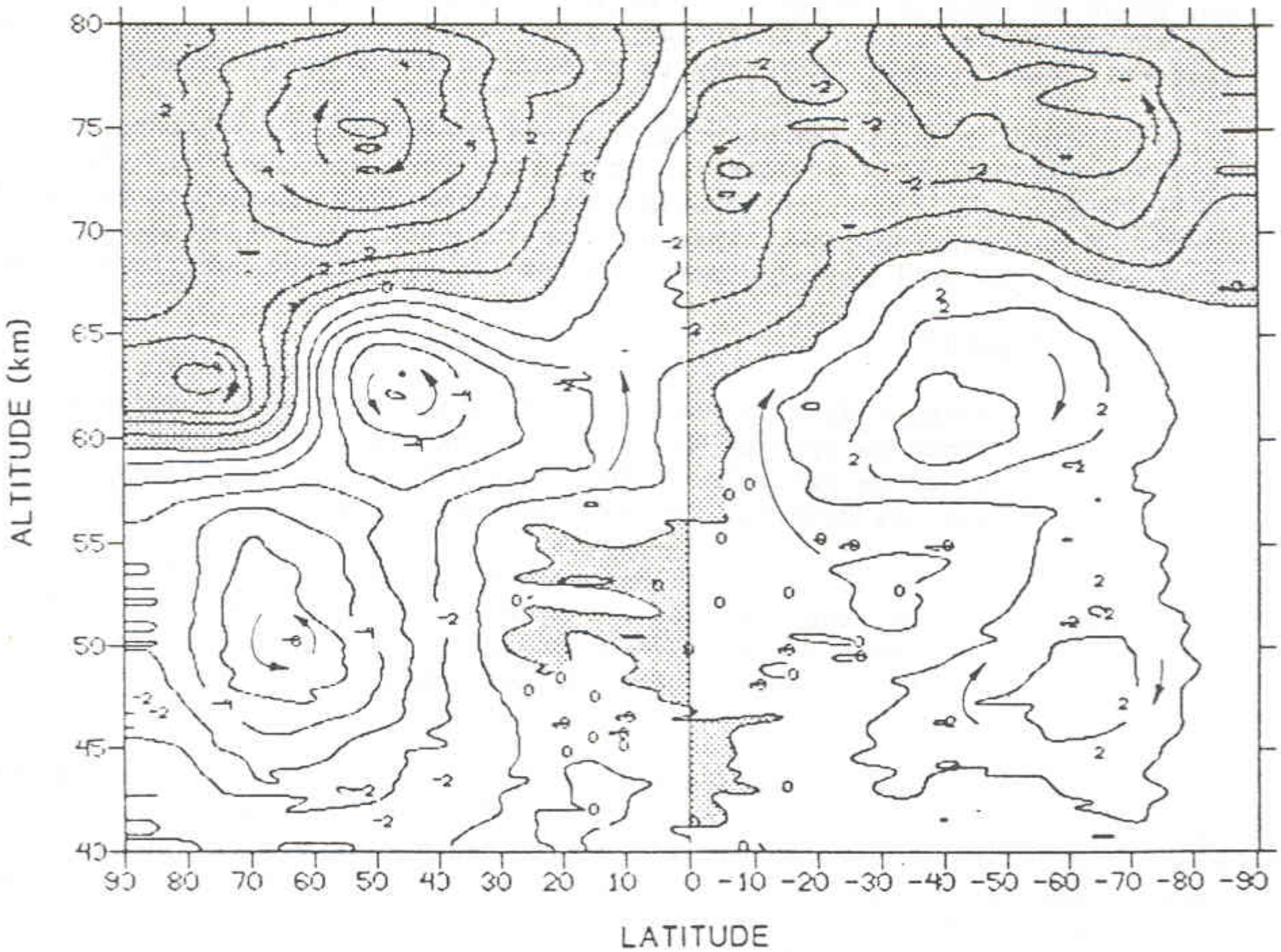


Fig. 8. Angle between isobaric and isosteric surfaces (thousandths of a degree) indicating the degree of barotropy and the existence of solenoids in the Venus atmosphere. In the northern hemisphere the negative sign implies a circulation in the sense of a right handed screw (out of the paper) while positive values indicate the same sense in the southern hemisphere (into the paper), leading to rising motion in the low latitudes below about 65 km and sinking motion in the polar latitudes below about 60 km. In the vicinity of 65 km level the observed (cloud tracking) average meridional flow is directed polewards in both the hemispheres, thus indicating acceleration of the flow due to solenoidal circulation.

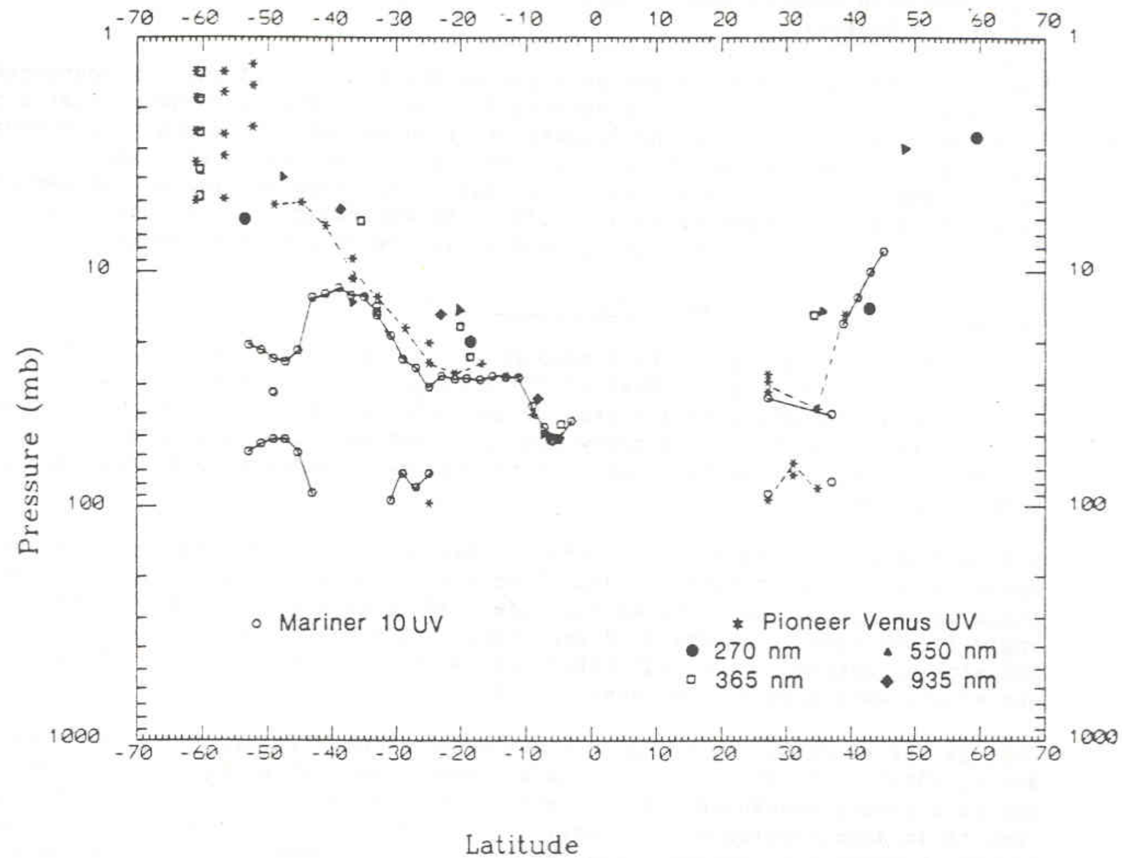


Fig. 7. Effective cloud level for the Mariner 10 (".") UV features and Pioneer UV and polarization features obtained by matching the measured average zonal component with the calculated balanced component. Possible locations below about 100 mb or about 60 km altitude are ruled out as they would then be undetectable in ultraviolet images.

Thermally Direct Cells inferred supported by the models of net flux - solar heating and observed thermal structure data

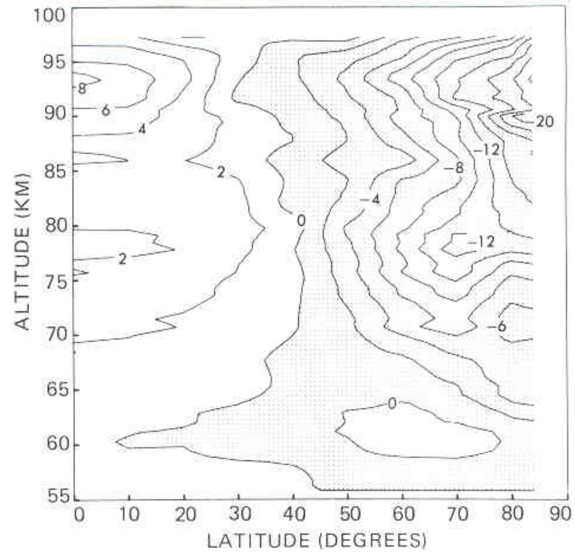


Figure 10. The net radiative heating rates (K day^{-1}) in the Venus mesosphere as a function of latitude and altitude for the PV OIR thermal structure (figure after Crisp 1989).

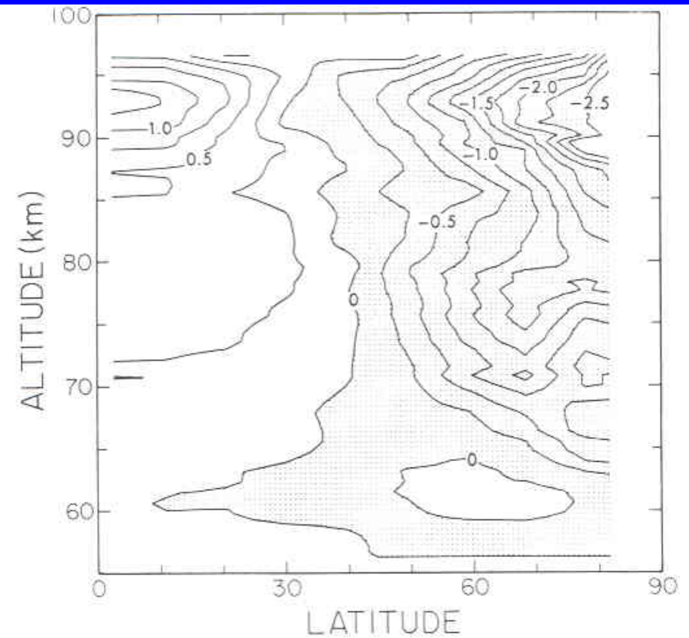
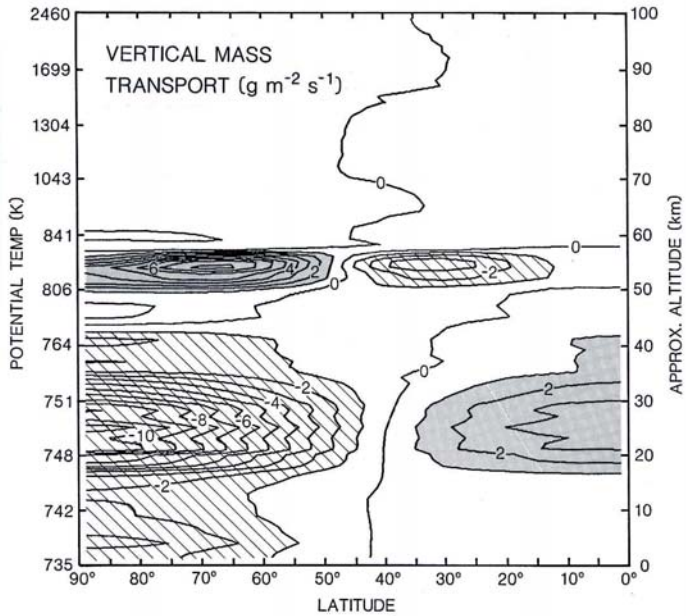
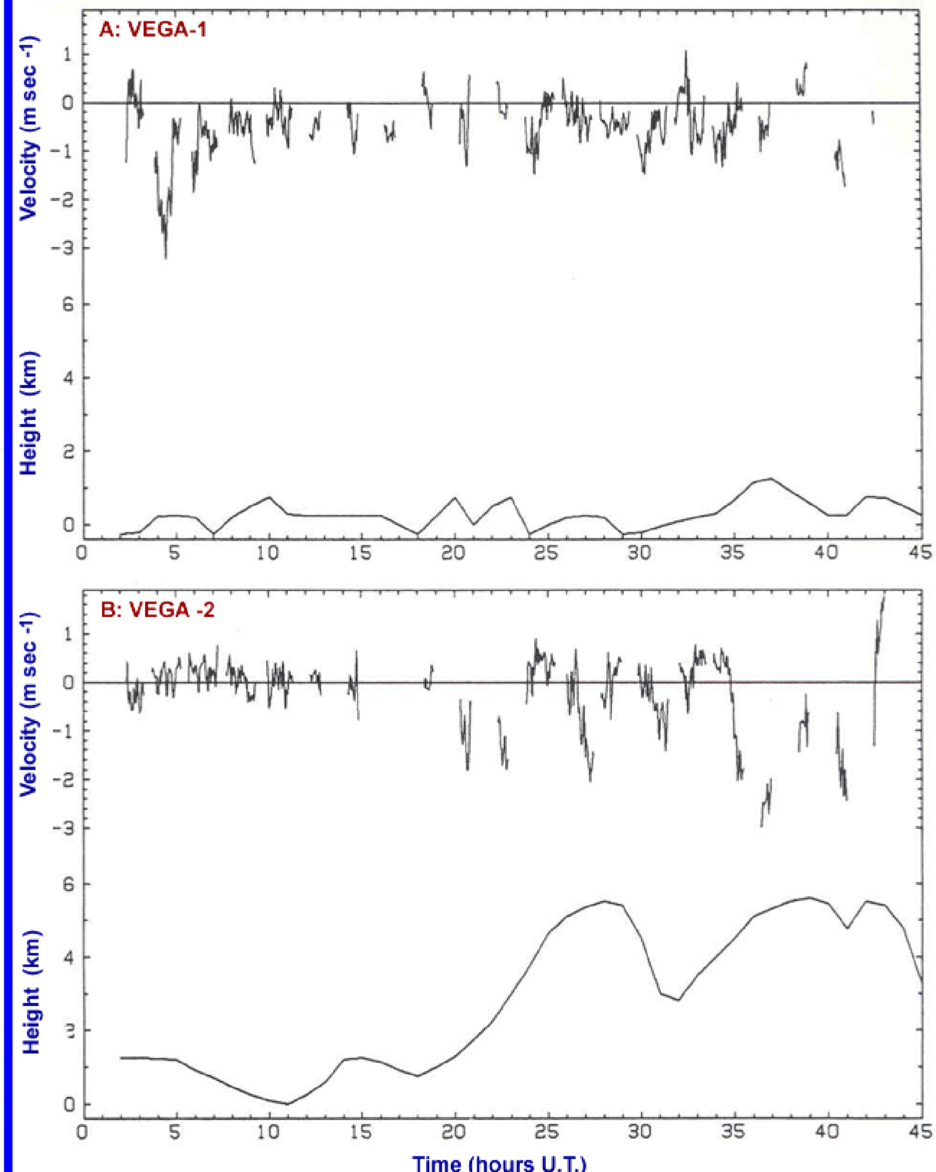


Figure 11. Vertical velocity distribution needed to produce adiabatic heating and cooling rates large enough to balance the net radiative drive for the PV OIR thermal structure (figure after Crisp 1983).



Crisp (1989); Revercomb (1989, Adv. Sp. Res.)



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

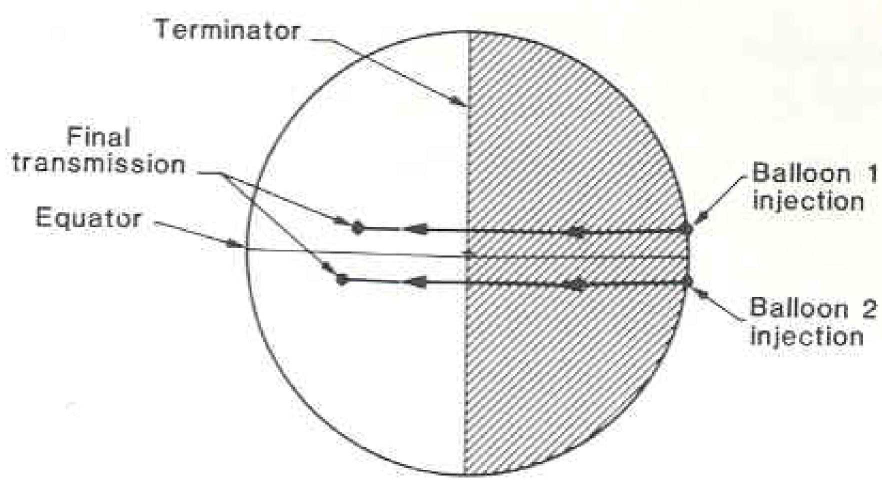
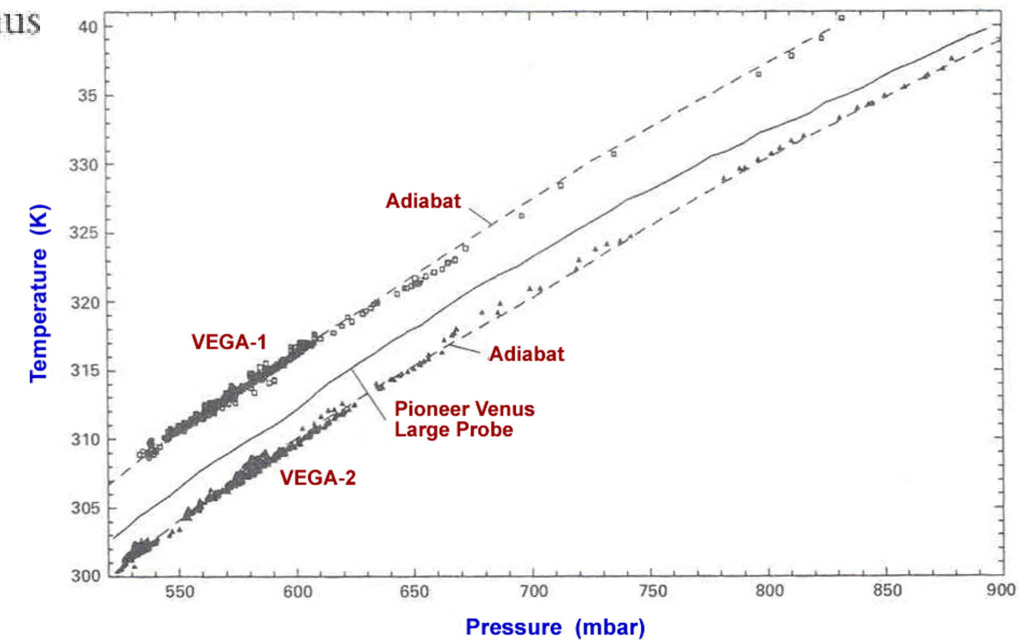


Fig. 2. Track of balloons across the face of Venus as viewed from Earth.



Measurements of temperature as a function of pressure from the two VEGA balloons compared with data from the Pioneer Venus Large Probe. The data from each balloon define a single curve of variation with small scatter. However, data from the two balloons are offset by 6.5 K at a given pressure and lie on either side of the Large Probe data. The balloons and the probe were within 7° of the equator at injection.

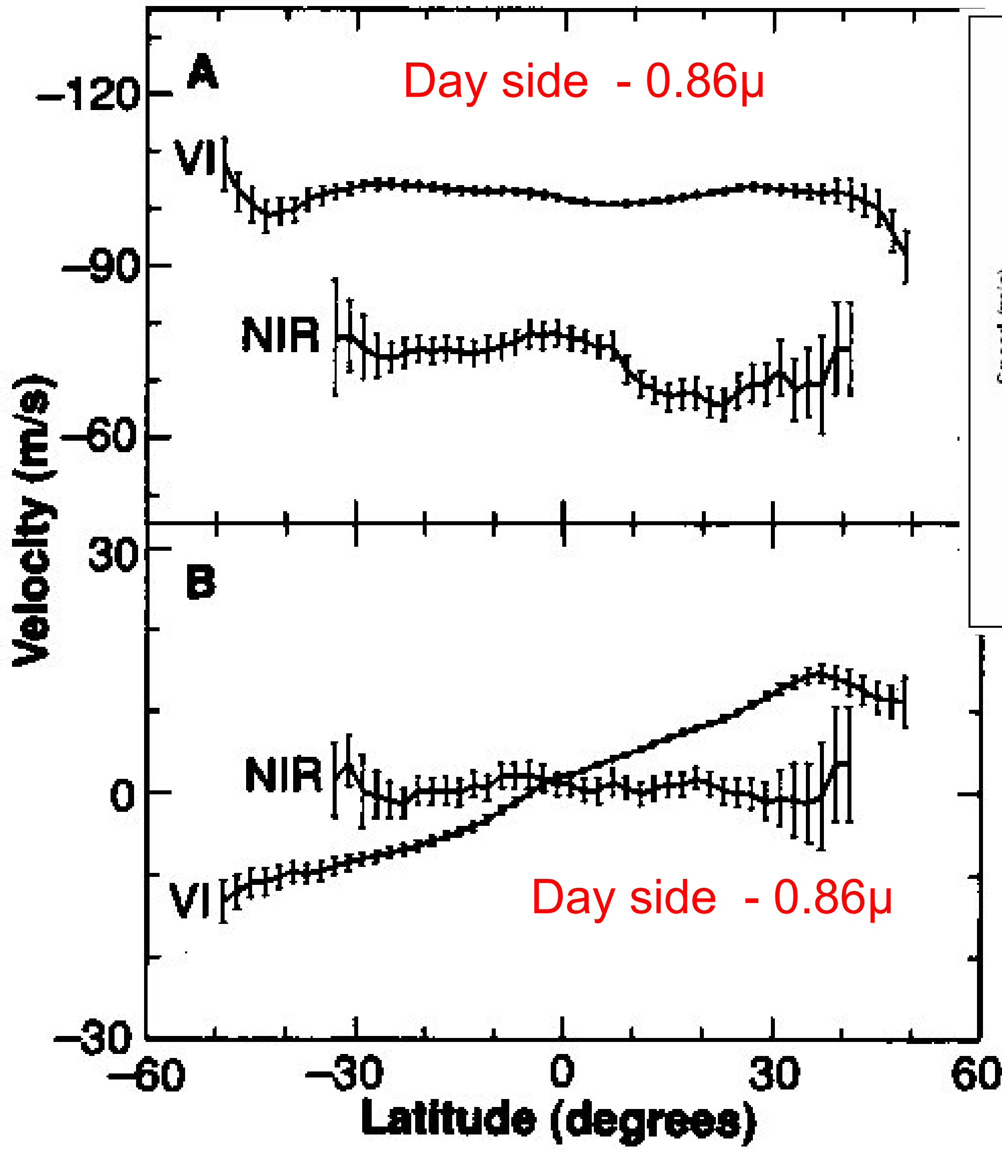
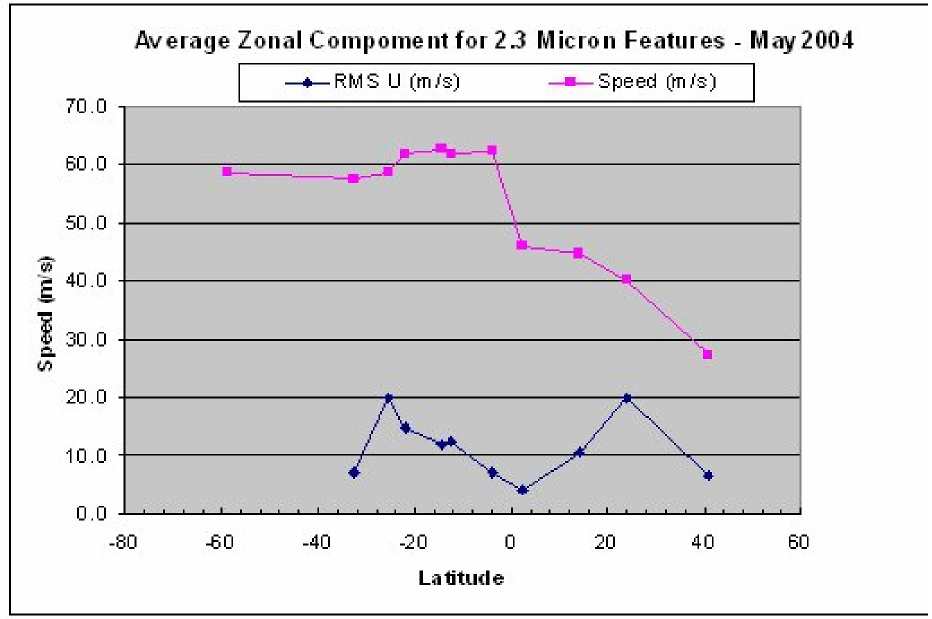


Fig. 5. Velocities of NIR and violet (VI) features as a function of latitude; (**A**) eastward, (**B**) northward. The vertical bars indicate the estimated error, based on the sample standard deviations within each 15° latitude averaging bin



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

↑(Limaye et al., 2006, BASI)

Near Infrared images provide cloud motions at other vertical levels

← Galileo SSI (Belton et al., 1991)

Energy Drive for Atmospheric Circulation

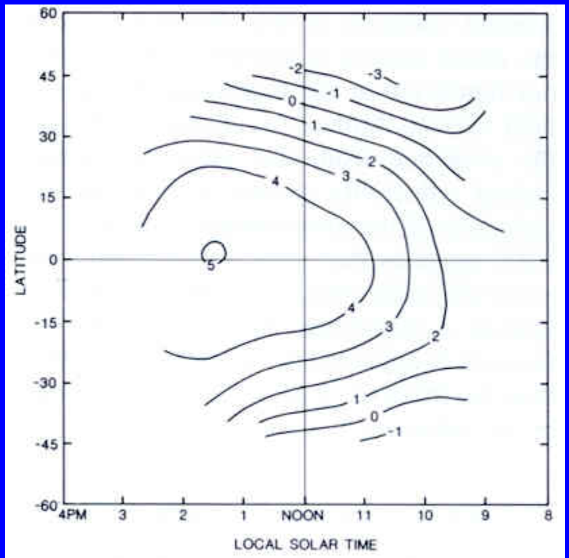
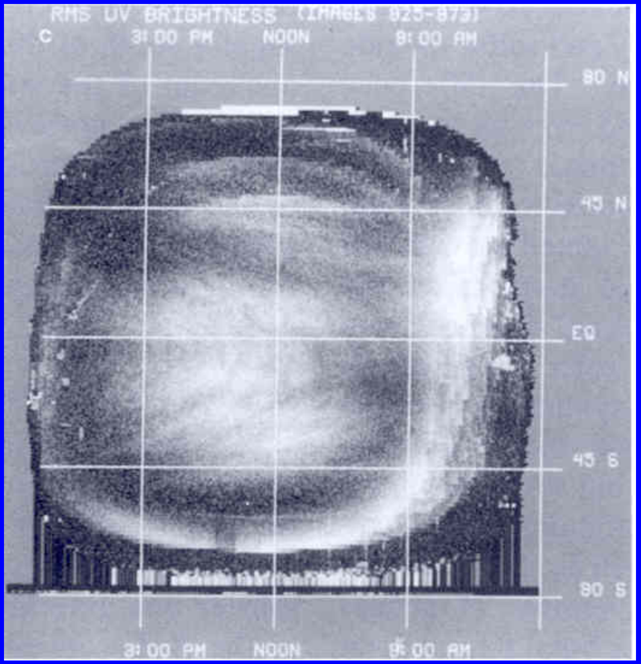
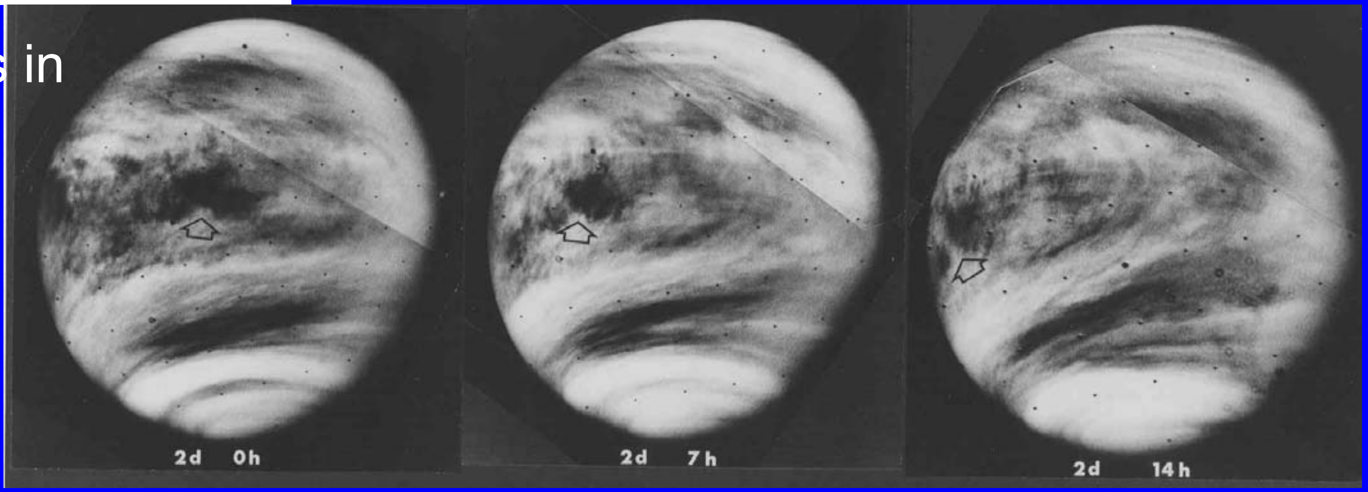


FIG. 4. (a) Horizontal divergence computed from fields of ⟨u⟩ and ⟨v⟩ by centered finite difference method and accounting for the convergence of meridians (in units of 10^{-6} sec^{-1}).

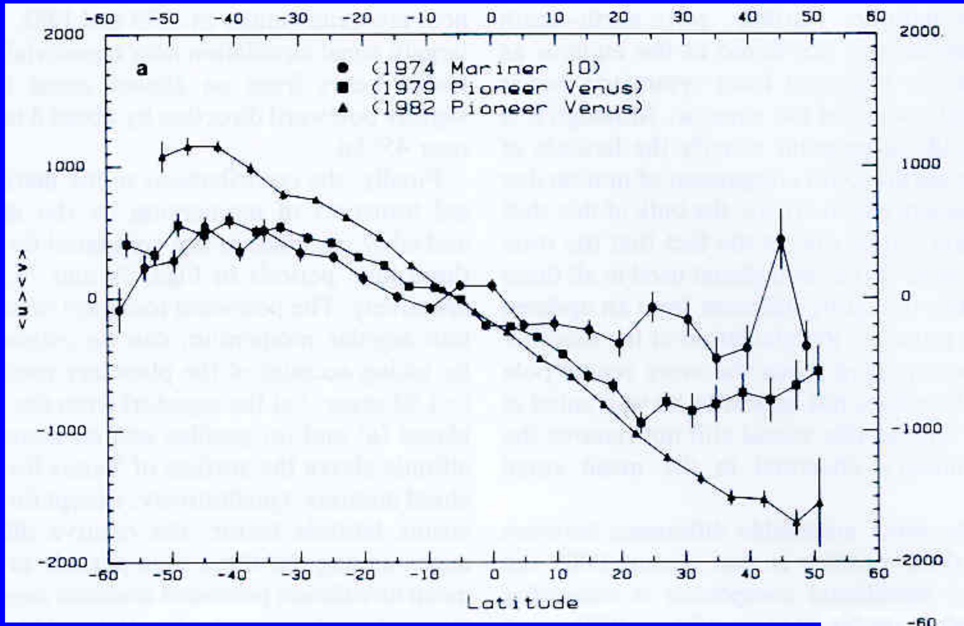
Velocity Divergence in a High Pressure Area (Sub-Solar Region)



Convective clouds in sub-solar region?



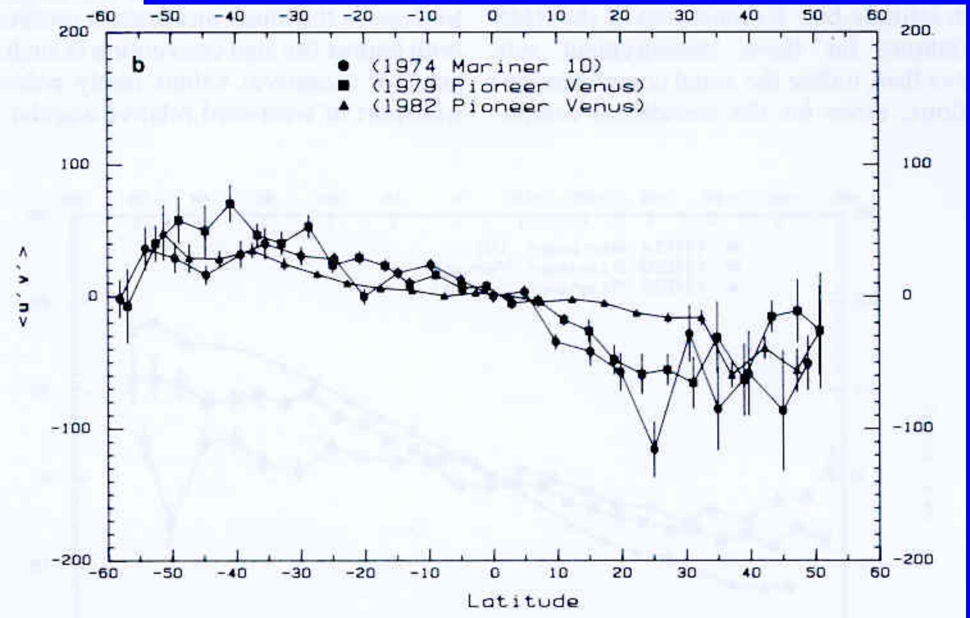
How is the angular momentum being supplied to low latitudes?



It is not at the UV cloud level

Meridional Transport of Angular Momentum by Mean Circulation

Meridional Transport of Angular Momentum by the Eddy Circulation



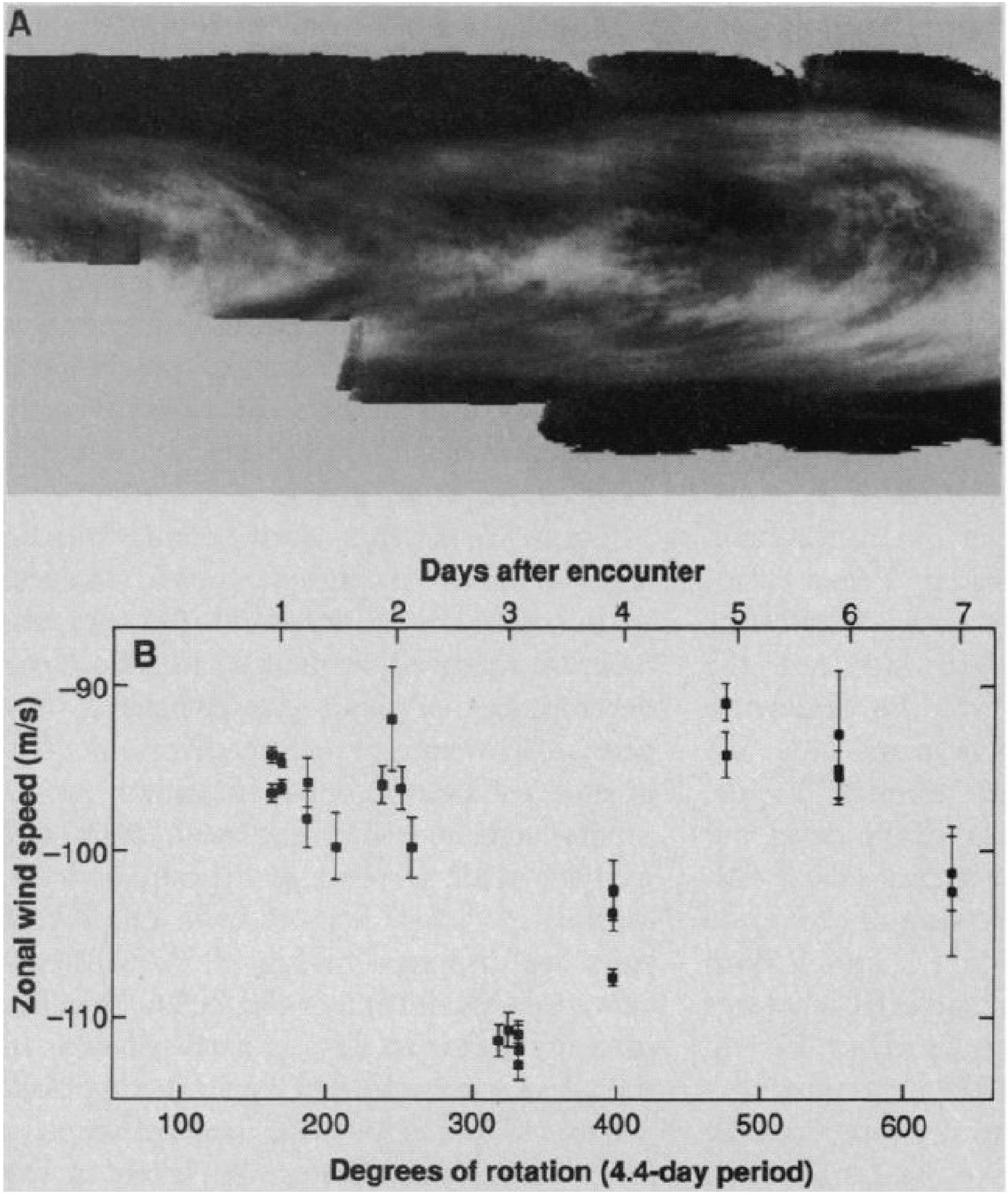


Fig. 4. (**A**) Cylindrical projection of a set of images taken over a 7-day period. A 4.4-day rotation period was adopted to define a longitude system that approximately moves with the equatorial clouds. The global dark and light pattern displays the "Y" and shows that there is a wavenumber-1 albedo variation. (**B**) The zonal wind speed, averaged over local times between 1 and 2 p.m. and latitudes 0° to 15°N, is displayed, also exhibiting a wavenumber-1 variation.

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?

Limitations of Spacecraft Data

- *Mariner images lacked long term coverage and limited phase angle coverage (Winds on day side only).*
- *Pioneer Venus Orbiter provided longevity but poor temporal and spatial coverage and biased in phase angle due to orbital geometry (day side only)*
- *Very few features available to track in high latitudes*
- *Observations at other wavelengths (Polarimetry) of low spatial and temporal resolution*
- *Concurrent observations of thermal structure and trace species lacking*

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)*

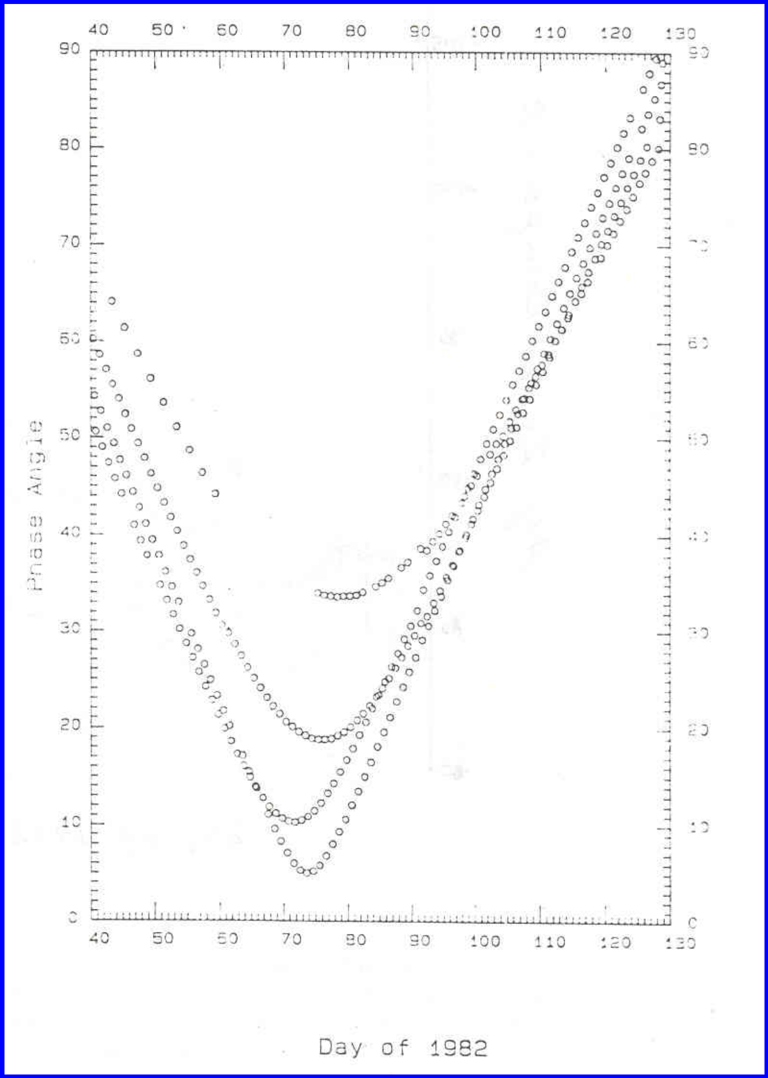
What don't we know

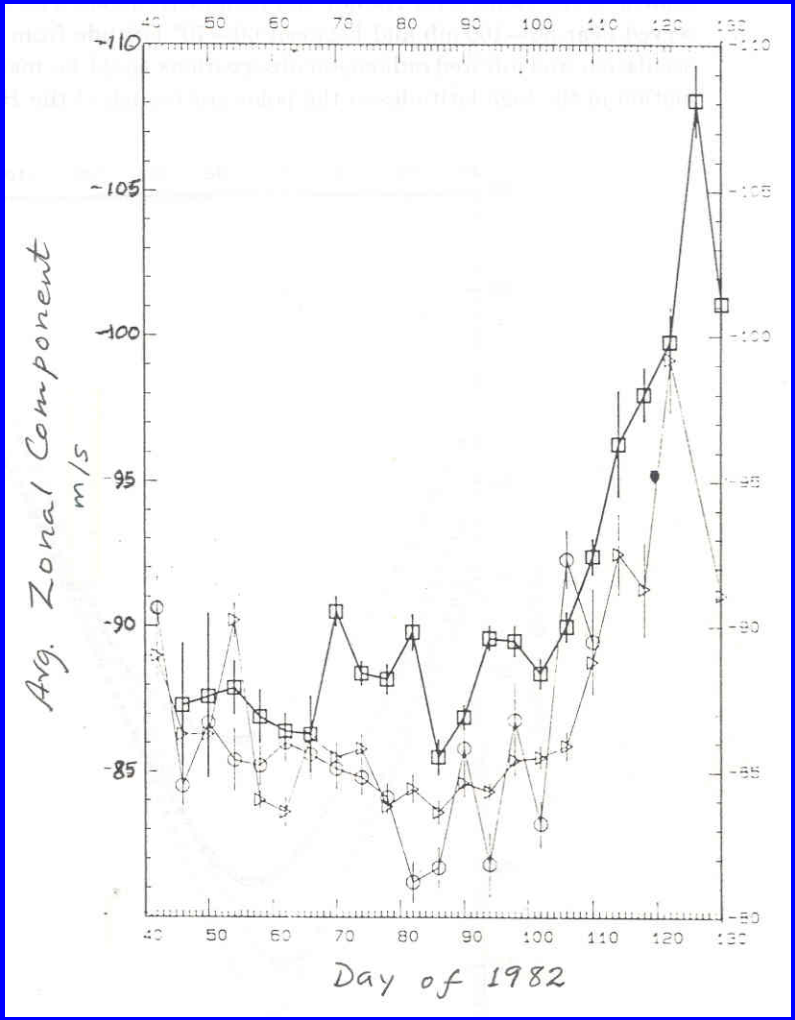
- Angular Momentum Balance
- Transport of Heat
- Transport of Trace Species
- Role of thermal tides and gravity/planetary scale waves
- Surface/Atmosphere Interaction

Difficulties in synthesis of data

- Spatial, temporal coverage and resolution very different
- No significant night side observations of circulation available to date
- 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)

Orbital Geometry Constrains Phase Angle Coverage Over Time





Recent Efforts

- Numerical Modeling

  Yamamoto and Takahashi, JAS, February 2003

  Read and colleagues (UK)
- Earth Based Near Infrared Observations

  Coordinated observations from IRTF, NOT, HCT, Mt. Abu, APO and AAT
- Amateur Imaging (UV)

Summary

Compared to Earth, for a 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.

How?

Tony/Jerry's Questions

- Is there a single Hadley Cell? – *likely*
- How far poleward does the Hadley Cell extend? – *to the poles, at least at UV cloud level*
- *What kind of waves accomplish the equatorward angular momentum transport?*

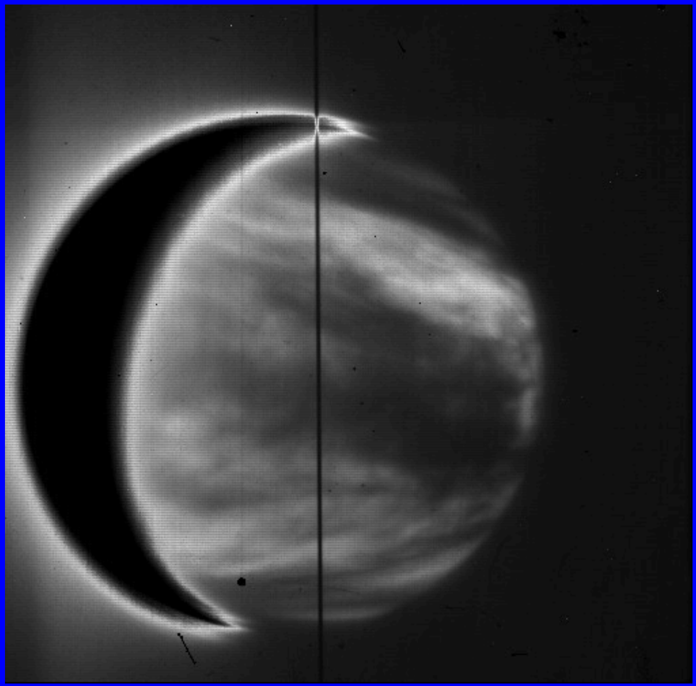
  Planetary scale/Kelvin waves? - ???

  Thermal Tides – possibly

  Instabilities – Barotropic?

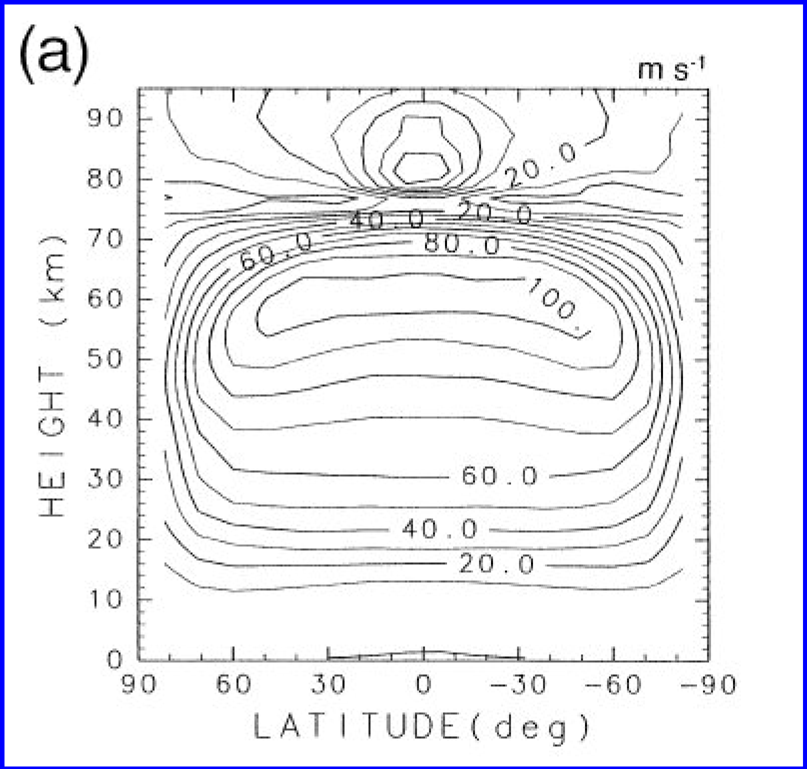
  Small scale gravity waves? – don't know

Recent 2.35 micron images

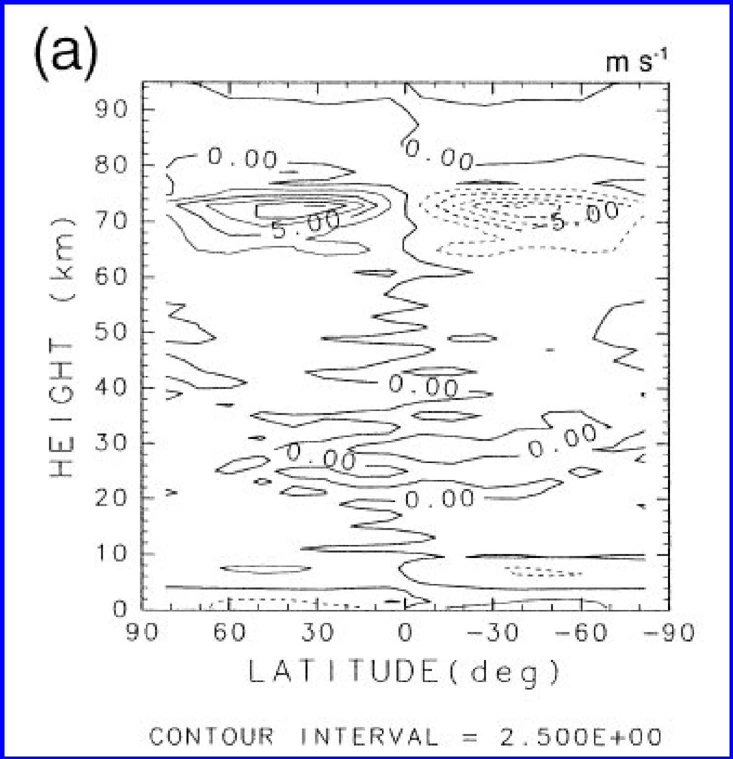


IRTF 4-5 July 2004

Animation of NOT, Mt. Abu, HCT and NOT images from May 2004



Zonal Flow



Meridional Flow

Yamamoto and Takahashi, 2003, JAS, February 2003

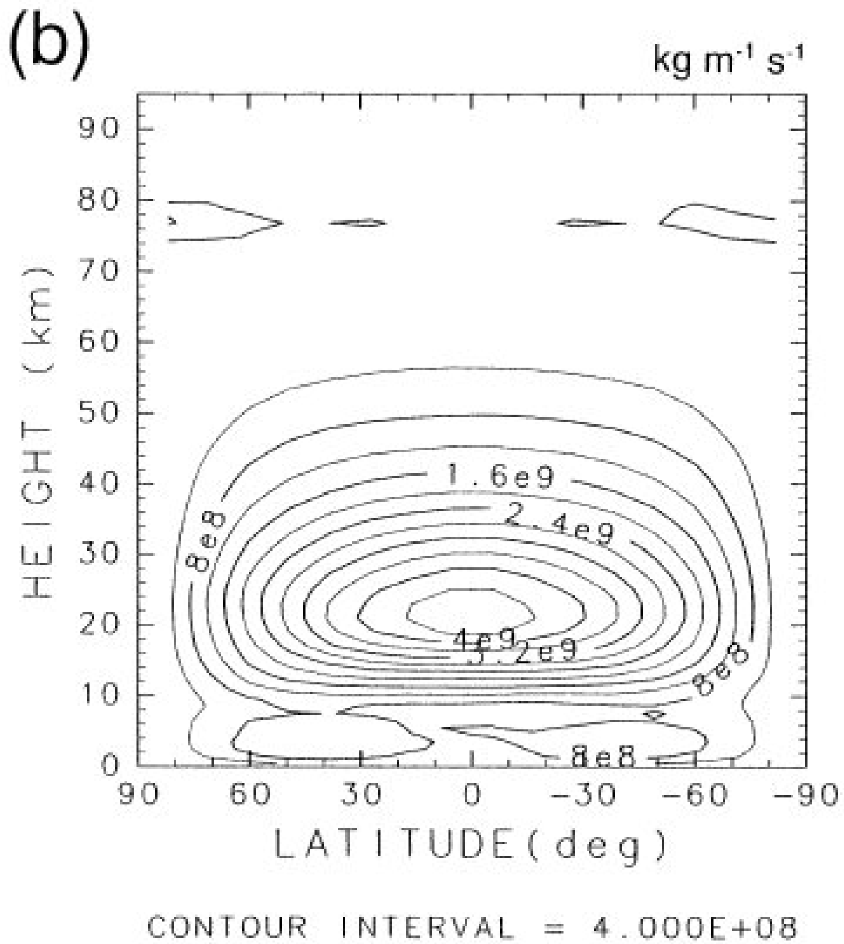


FIG. 4. Latitude–height cross sections of longitudinal average of (a) zonal flow ($m\ s^{-1}$) and (b) angular momentum density ($kg\ m^{-1}\ s^{-1}$), averaged over 117 days (one Venus day) on day 63 180.

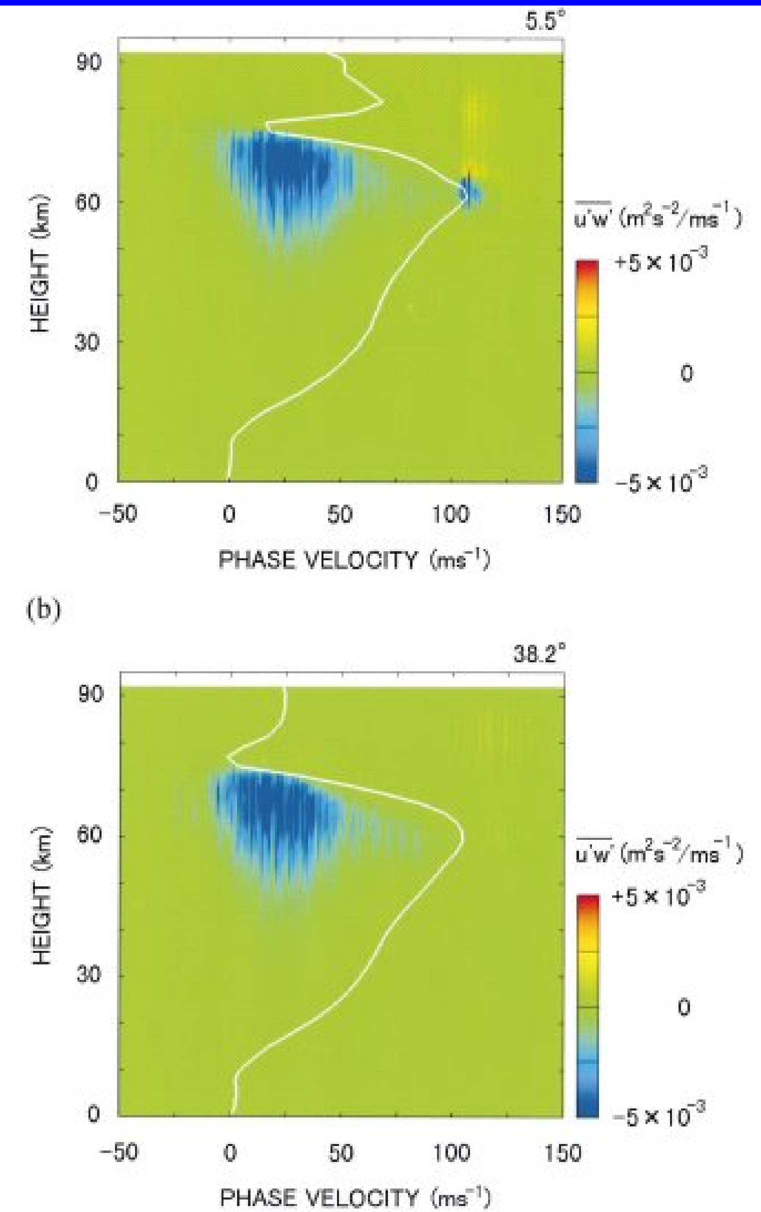


FIG. 13. Phase velocity–height cross sections of spectrum of $\overline{u'w'}$ at (a) 5.5° and (b) 38.2°, averaged over a sampling period of 4096 h from day 63 180.

Angular Momentum Density ↑

Spectrum of <u'w'> →

Understanding the Atmospheric Circulation in an average sense

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

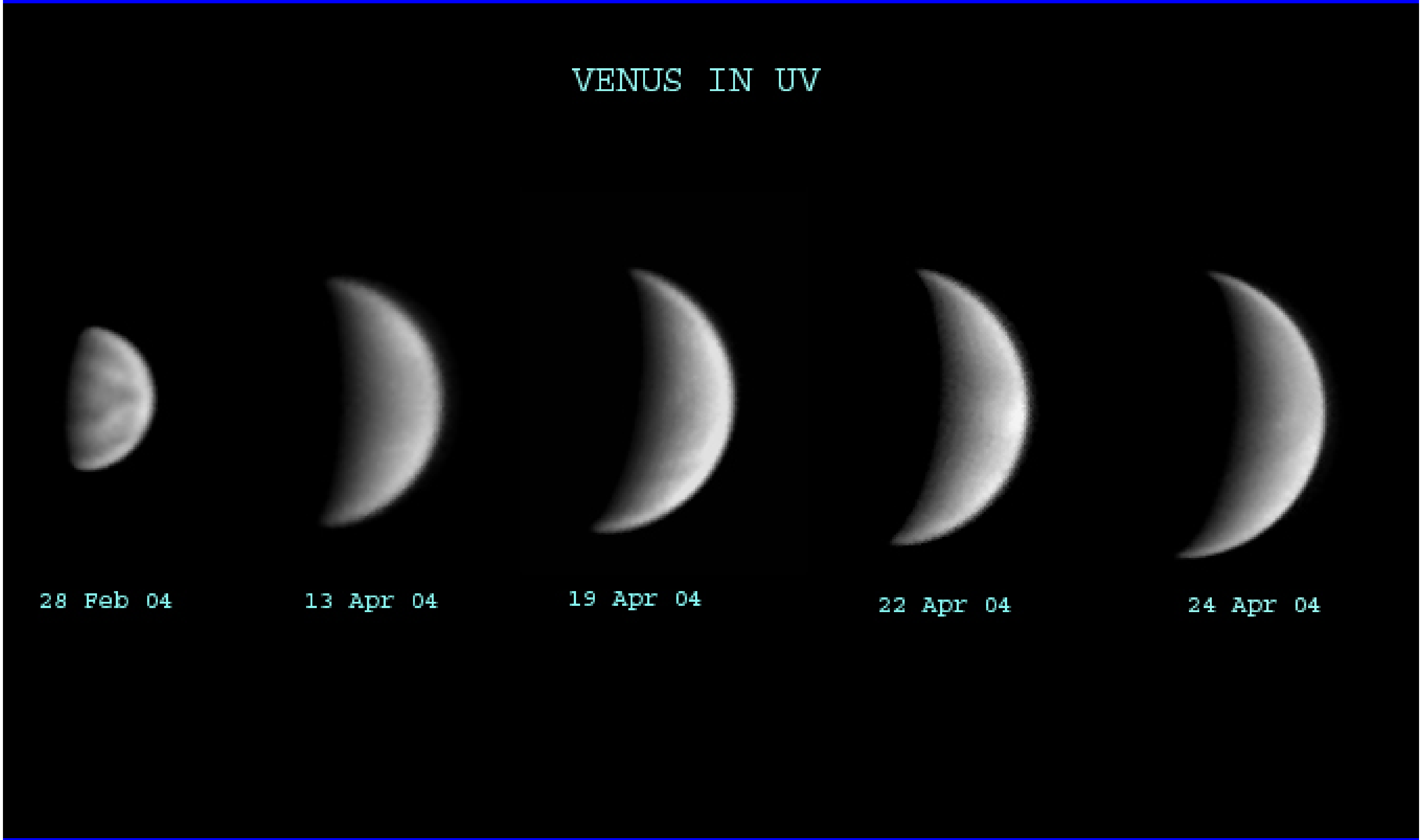
Latitudinal profiles with depth:

angular momentum transport

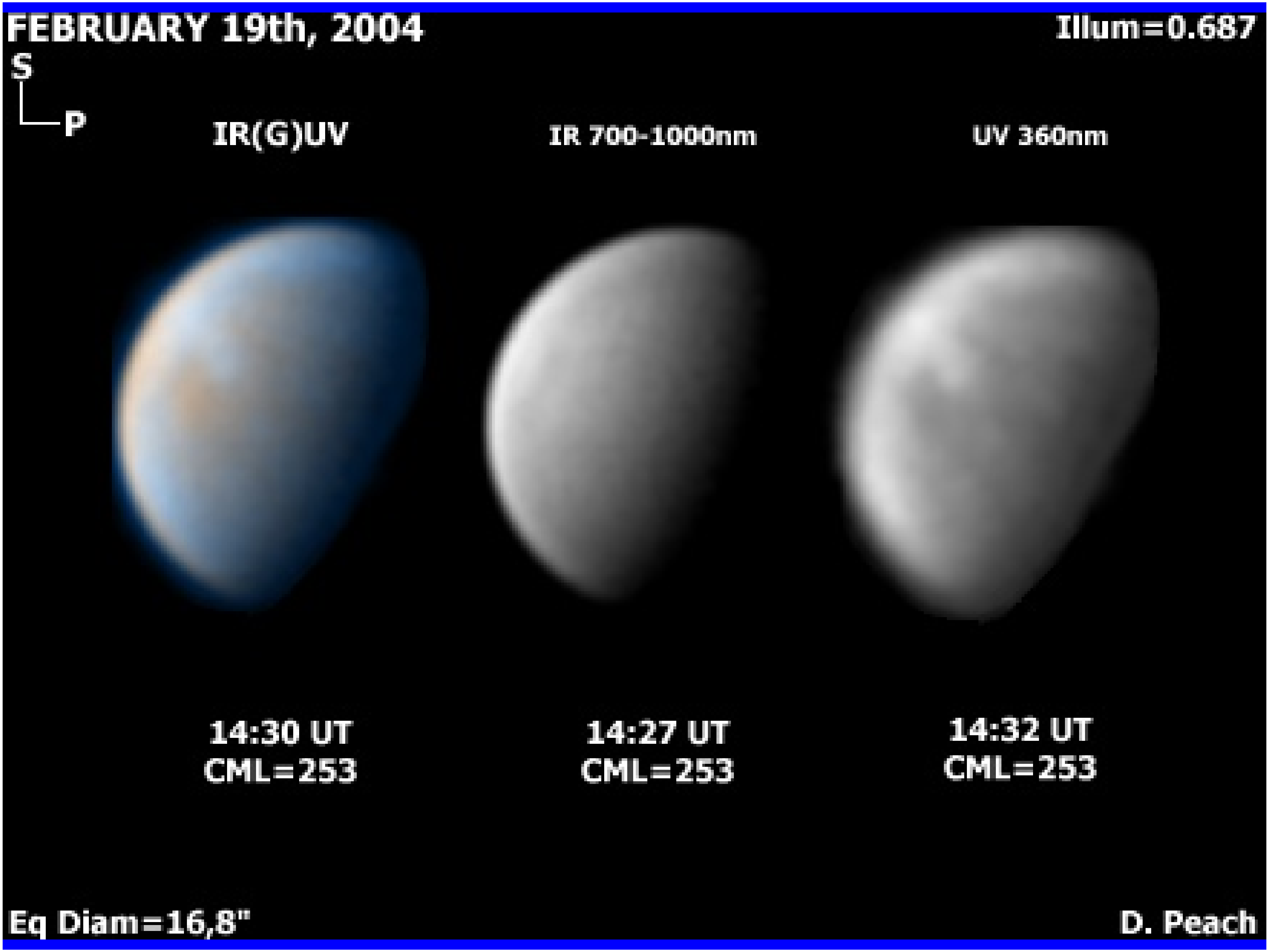
heat transport

trace species

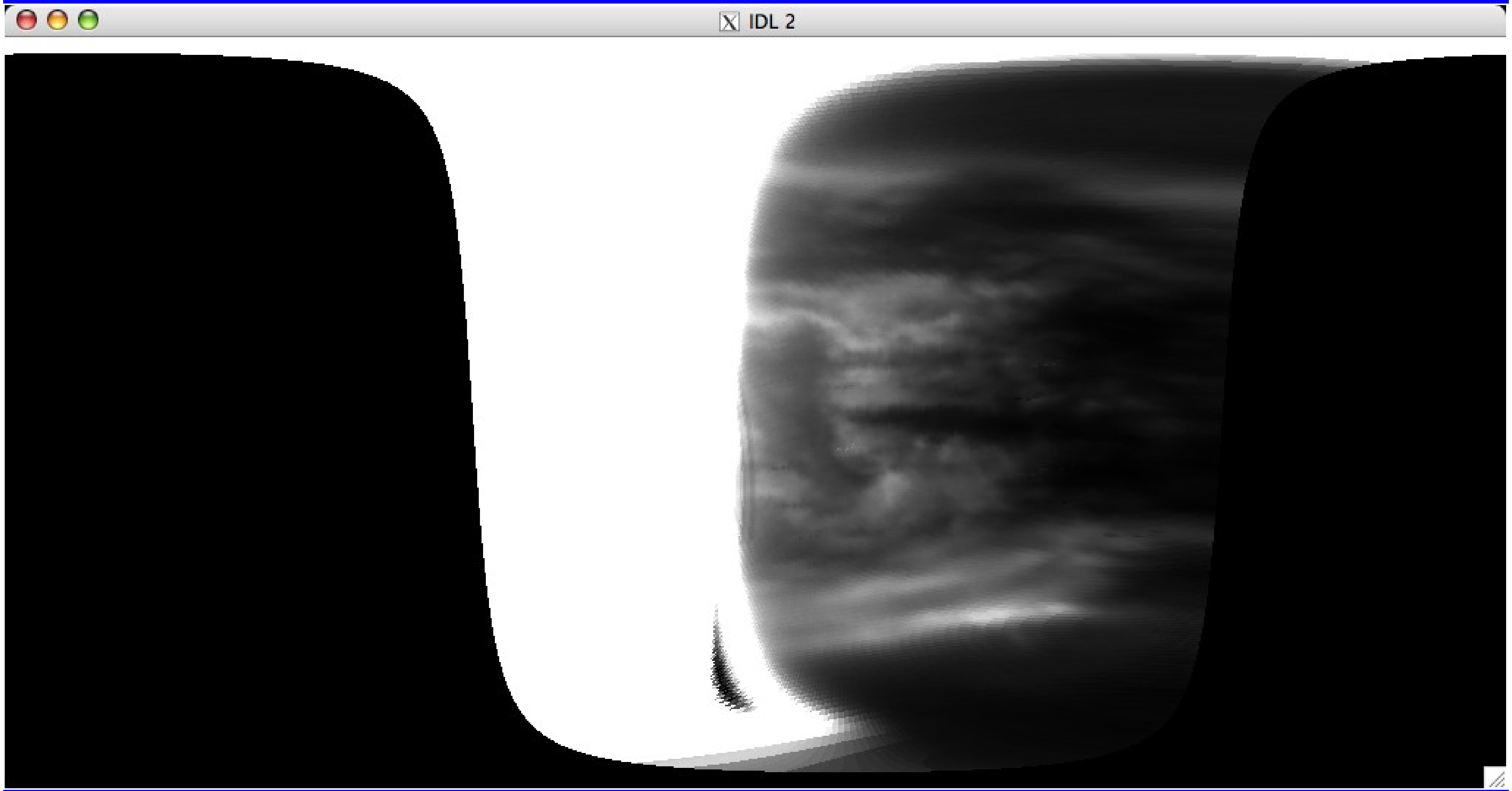
→ Need systematic observations (spatial and temporal coverage)



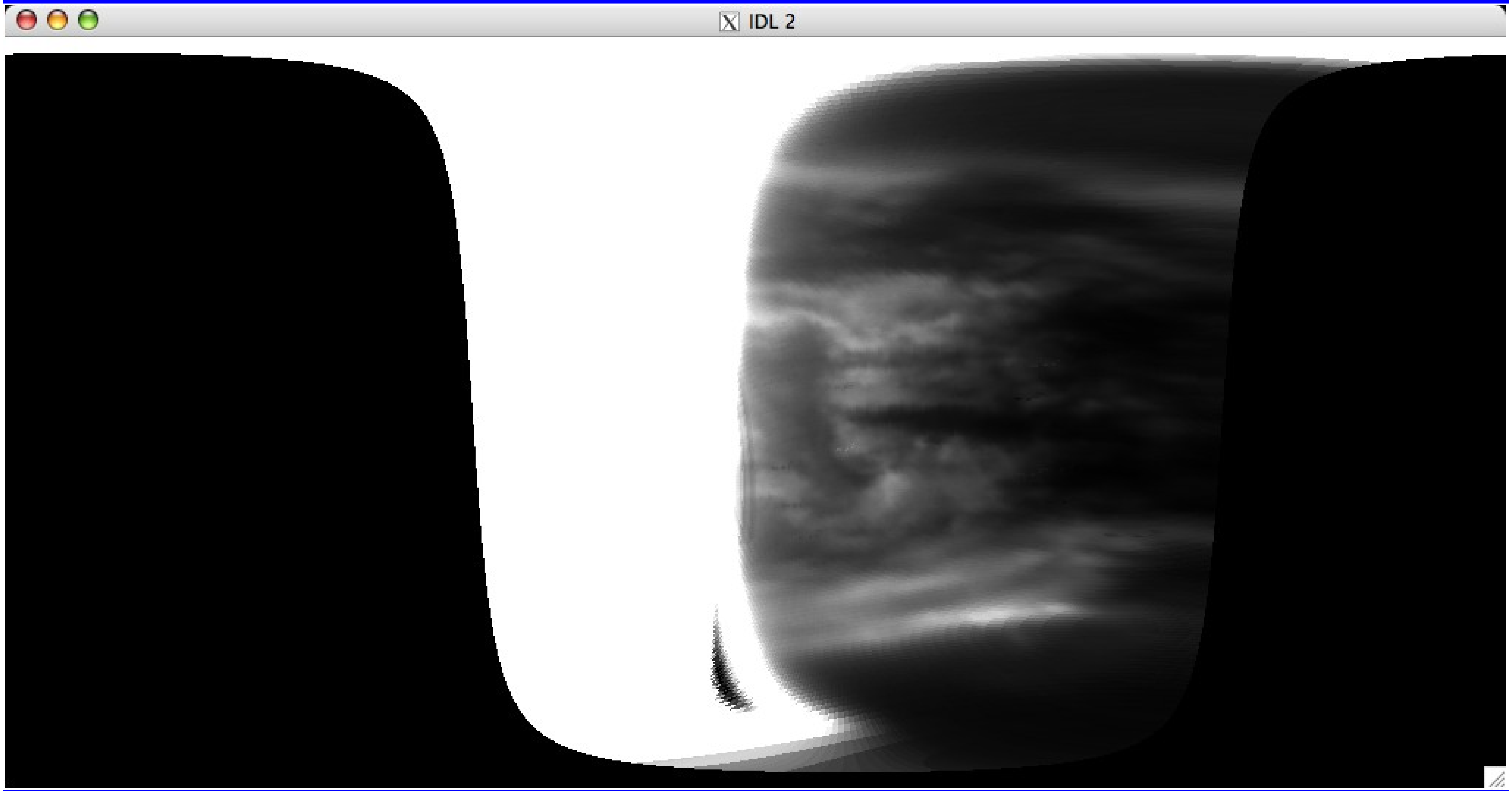
J. Cooper


FEBRUARY 19th, 2004
Illum=0.687
S
P
IR(G)UV
IR 700-1000nm
UV 360nm
14:30 UT
CML=253
14:27 UT
CML=253
14:32 UT
CML=253
Eq Diam=16,8"
D. Peach

IRTF 4 July 2004 K Filter



IRTF 13 July 2004 15:30 UT K Filter



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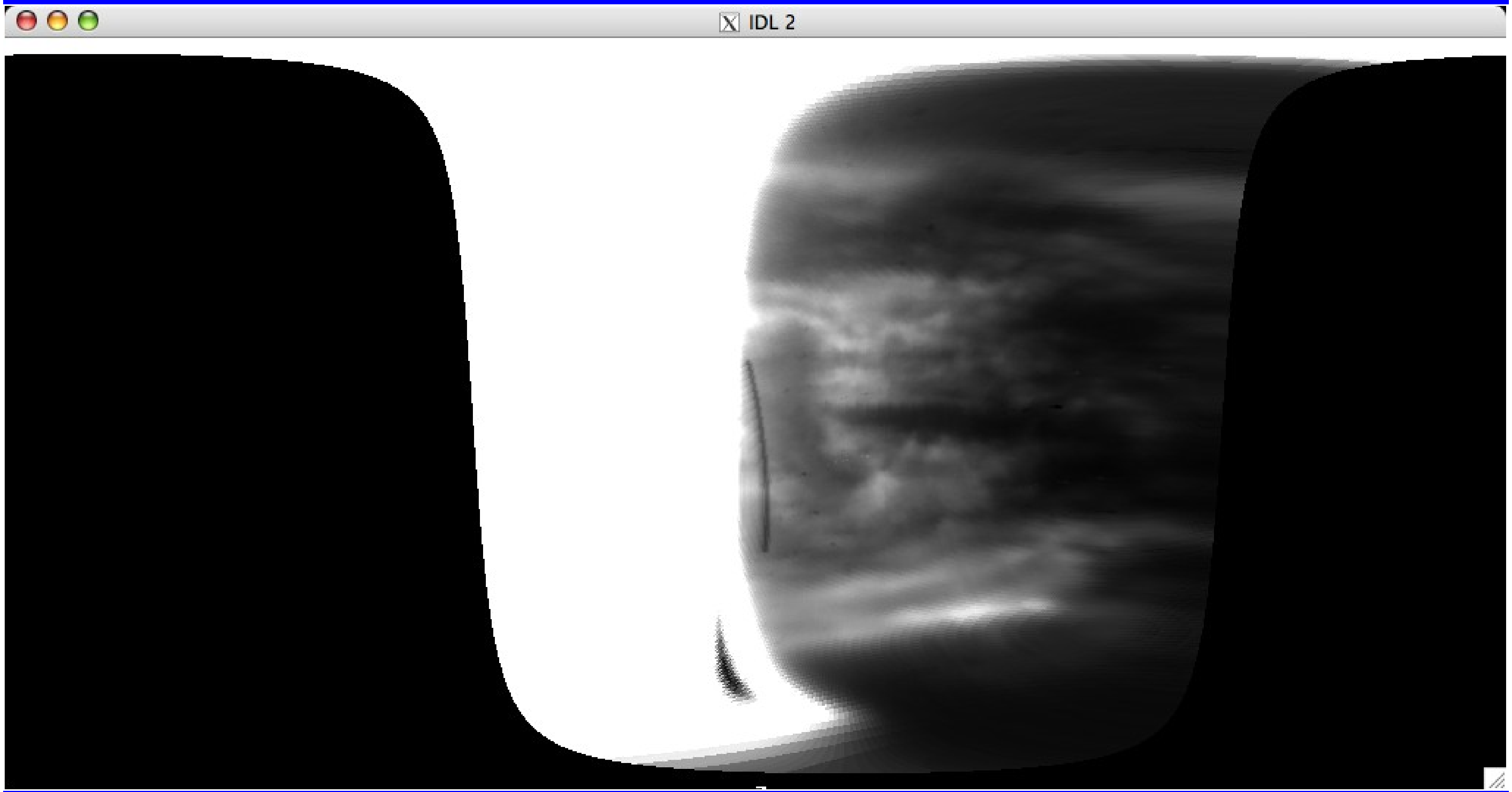
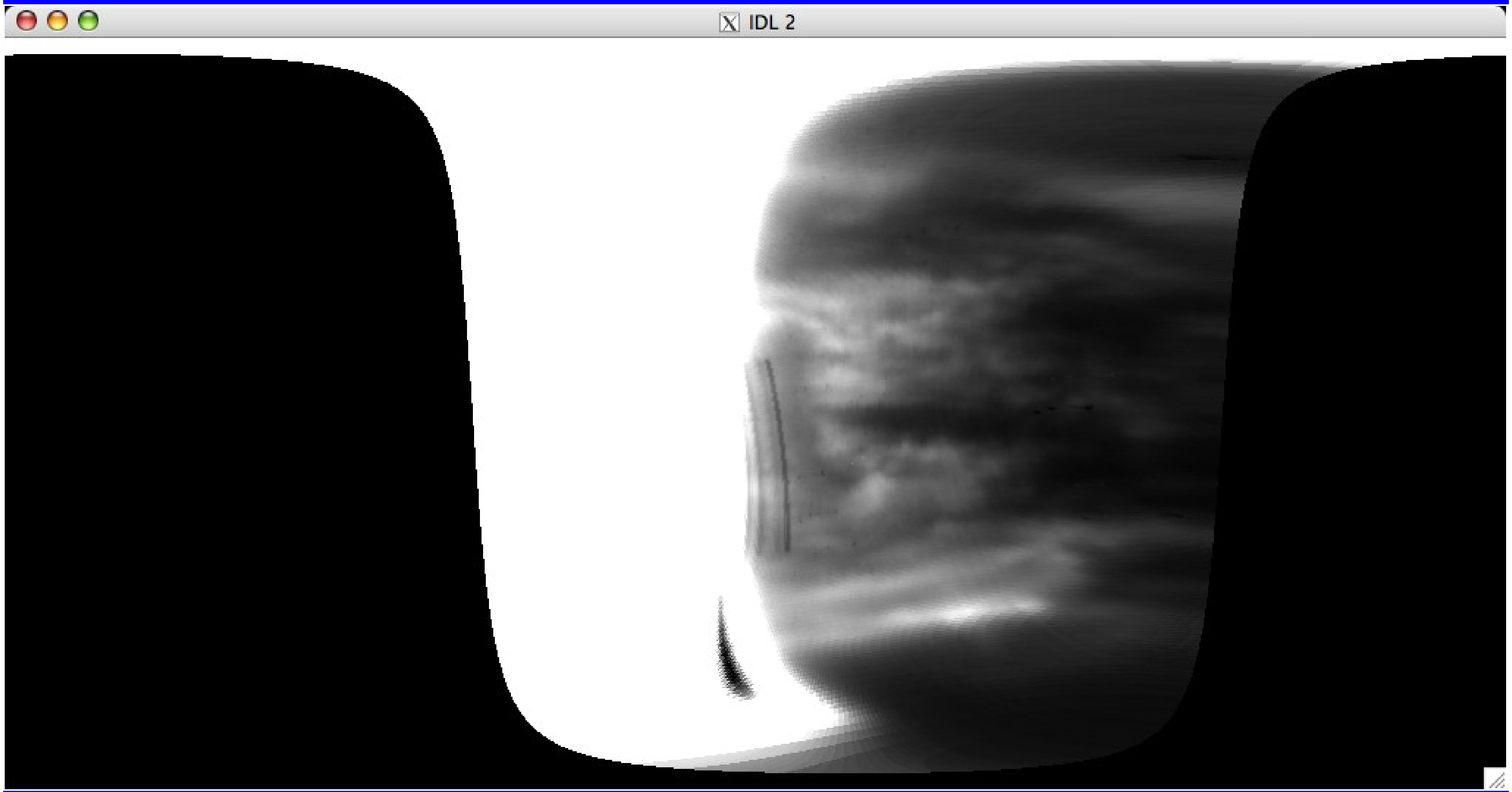
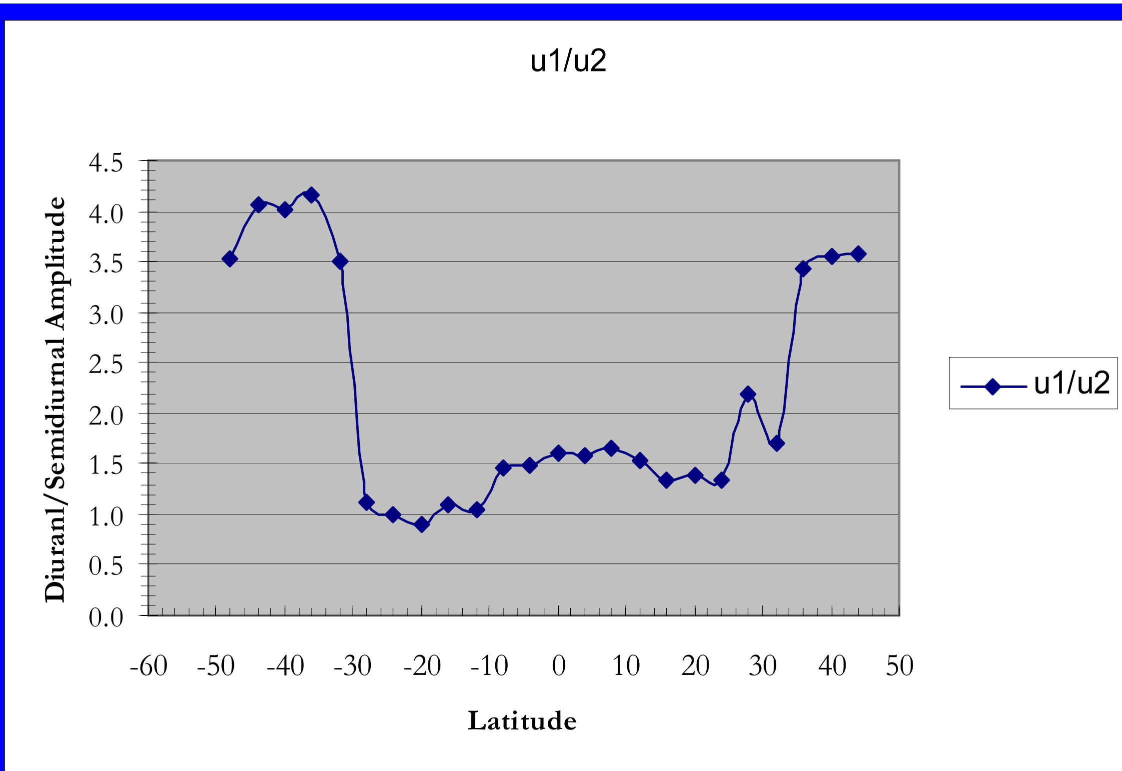


IRTF 13 July 2004 17:30 UT K Filter

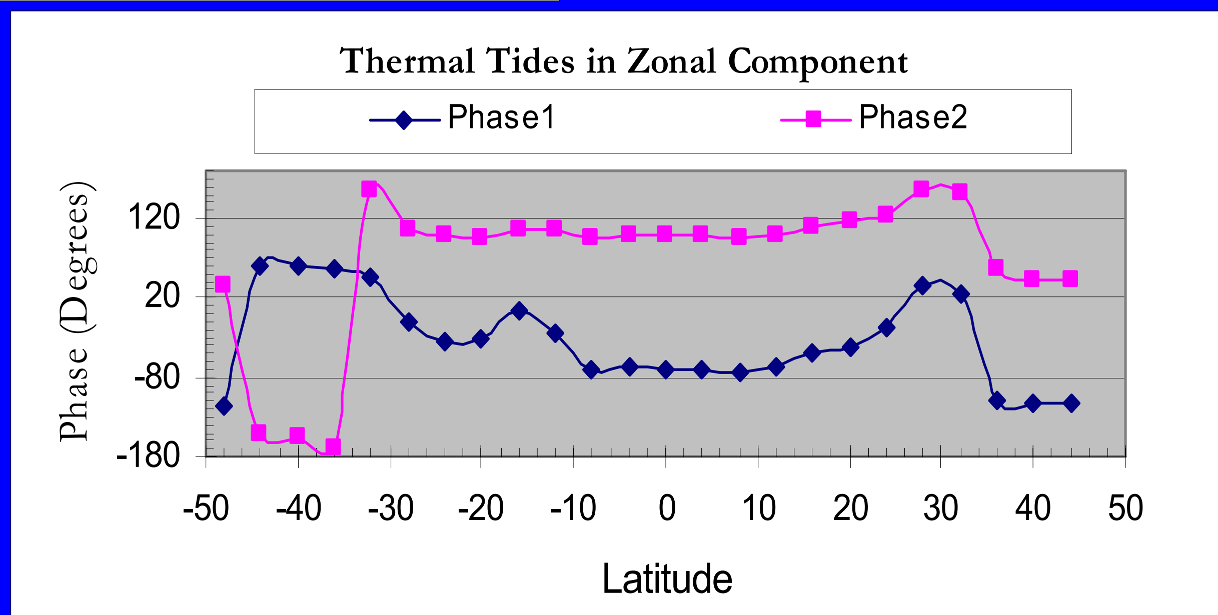


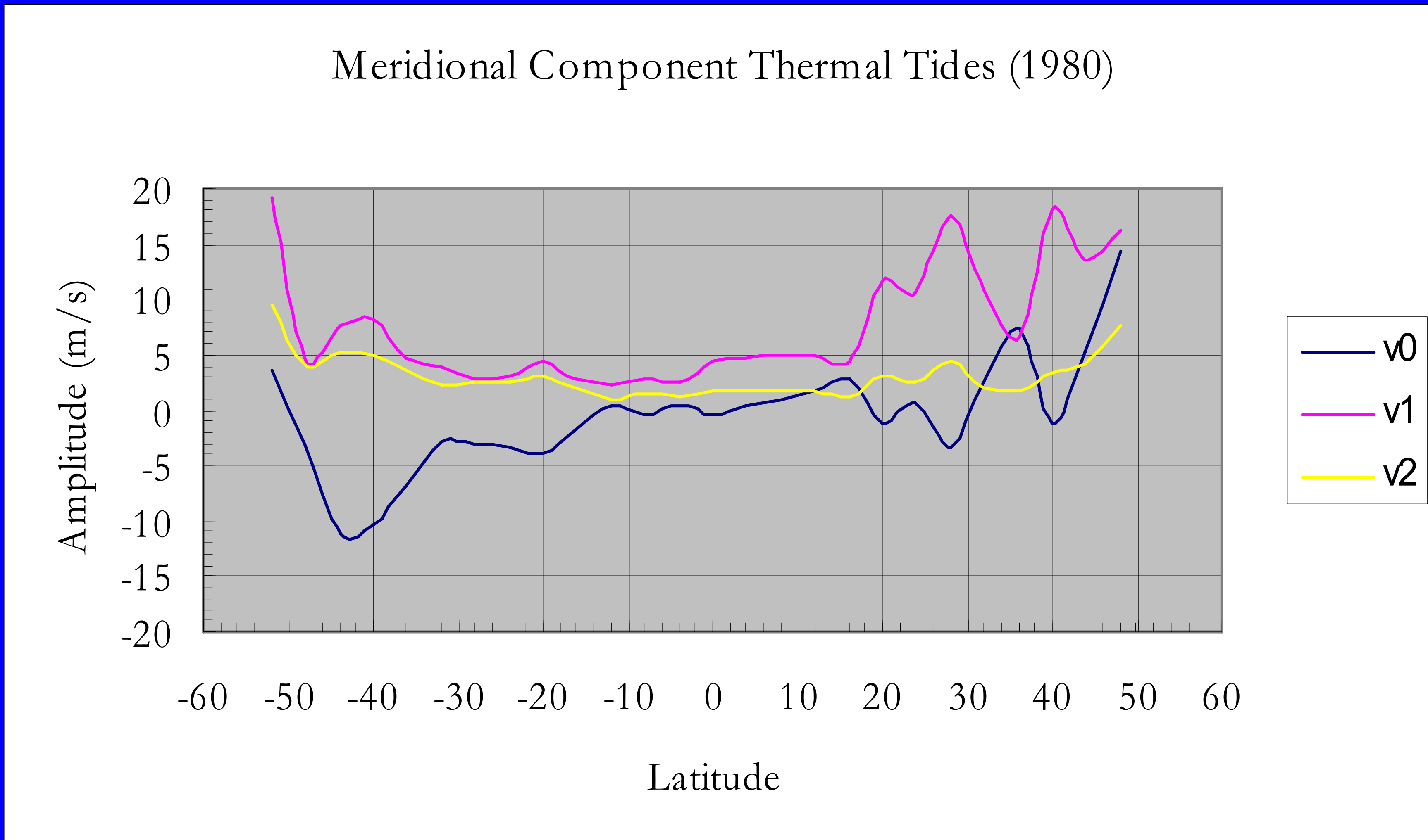
Systematic Observations: Future Missions

- Venus Express ~ (2006 – 2008)
- Venus Climate Orbiter (Japan) ~ 2011
- Atmospheric Probes ~ 2010 ?
- Surface Stations?

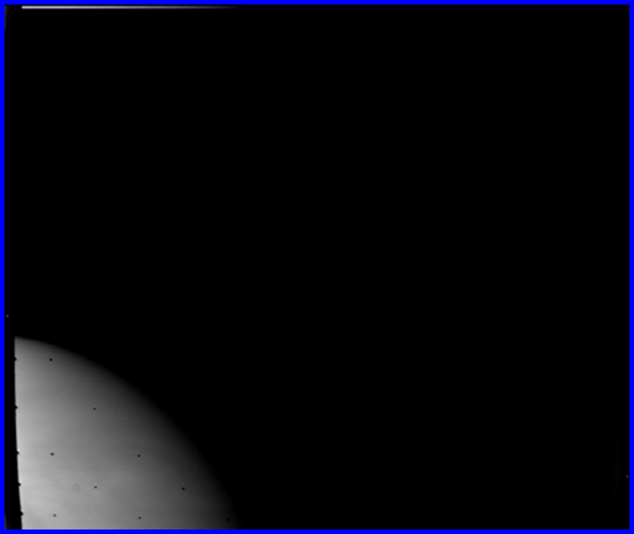


Observed Tidal Components likely inconsistent with expectations

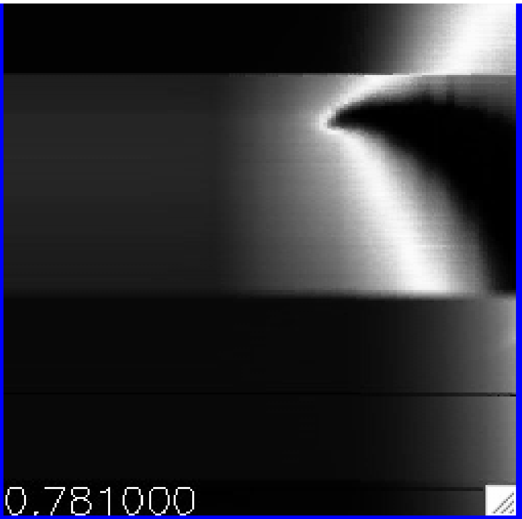


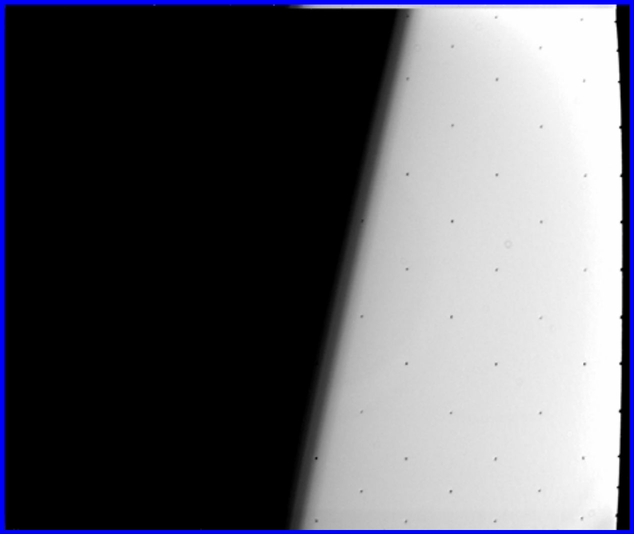


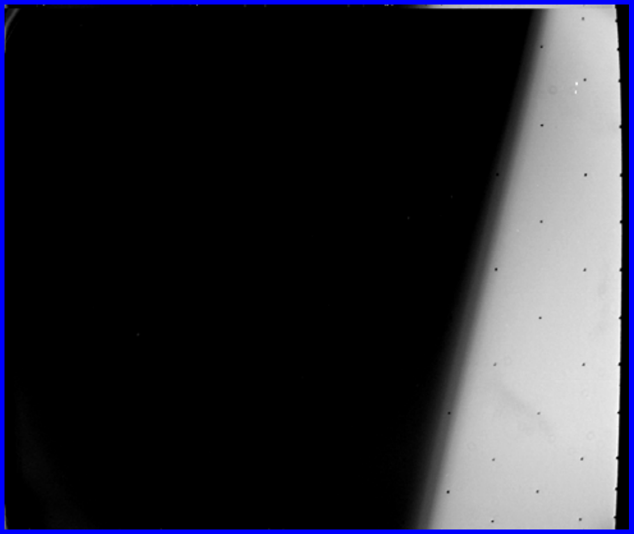
Meridional Component Thermal Tides (1980)
Amplitude (m/s)
20
15
10
5
0
-5
-10
-15
-20
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
Latitude
v0
v1
v2

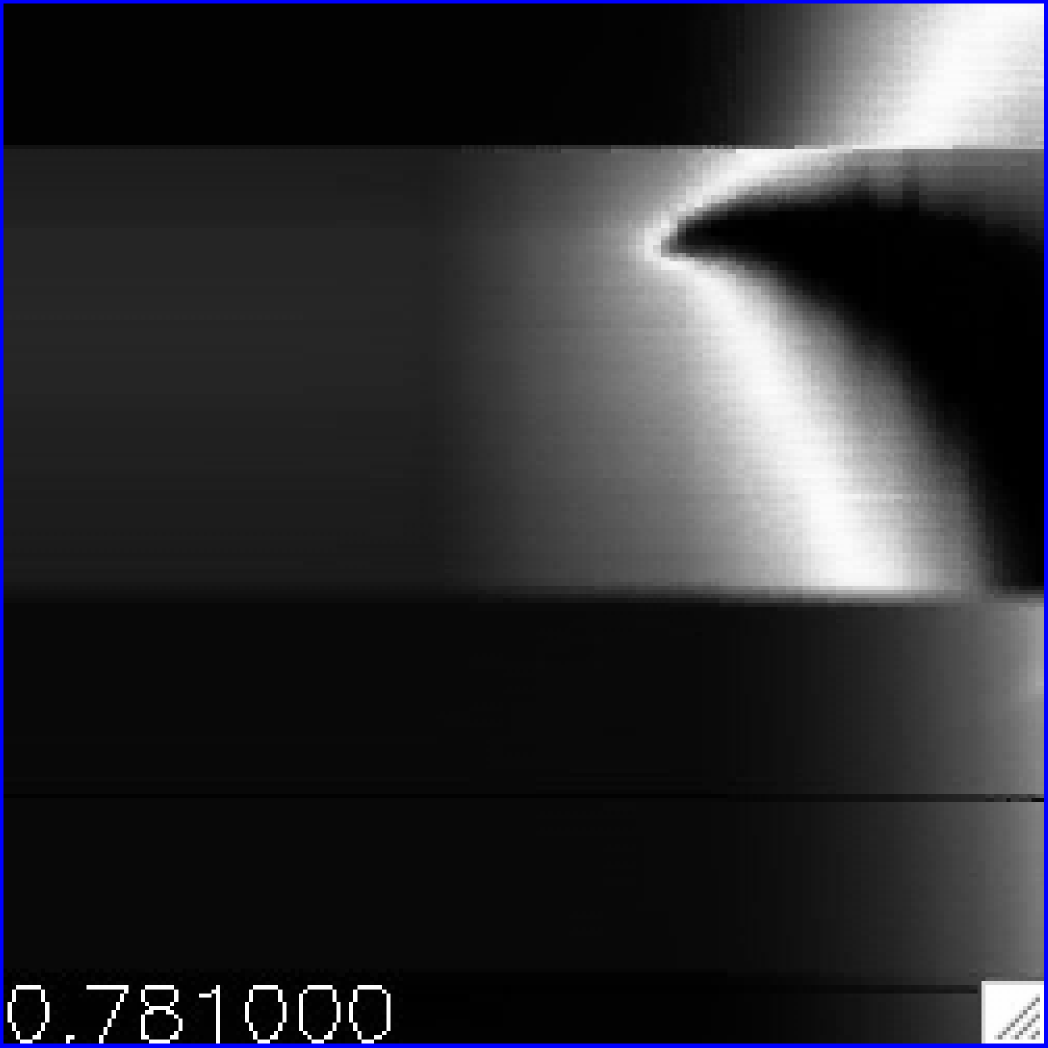



2004-05-03 21:44:04 0
may3_214404_082brcrsn.fits
0
210
240
270
300


0.781000







Spectral Animation – IRTF (Bullock and Young)

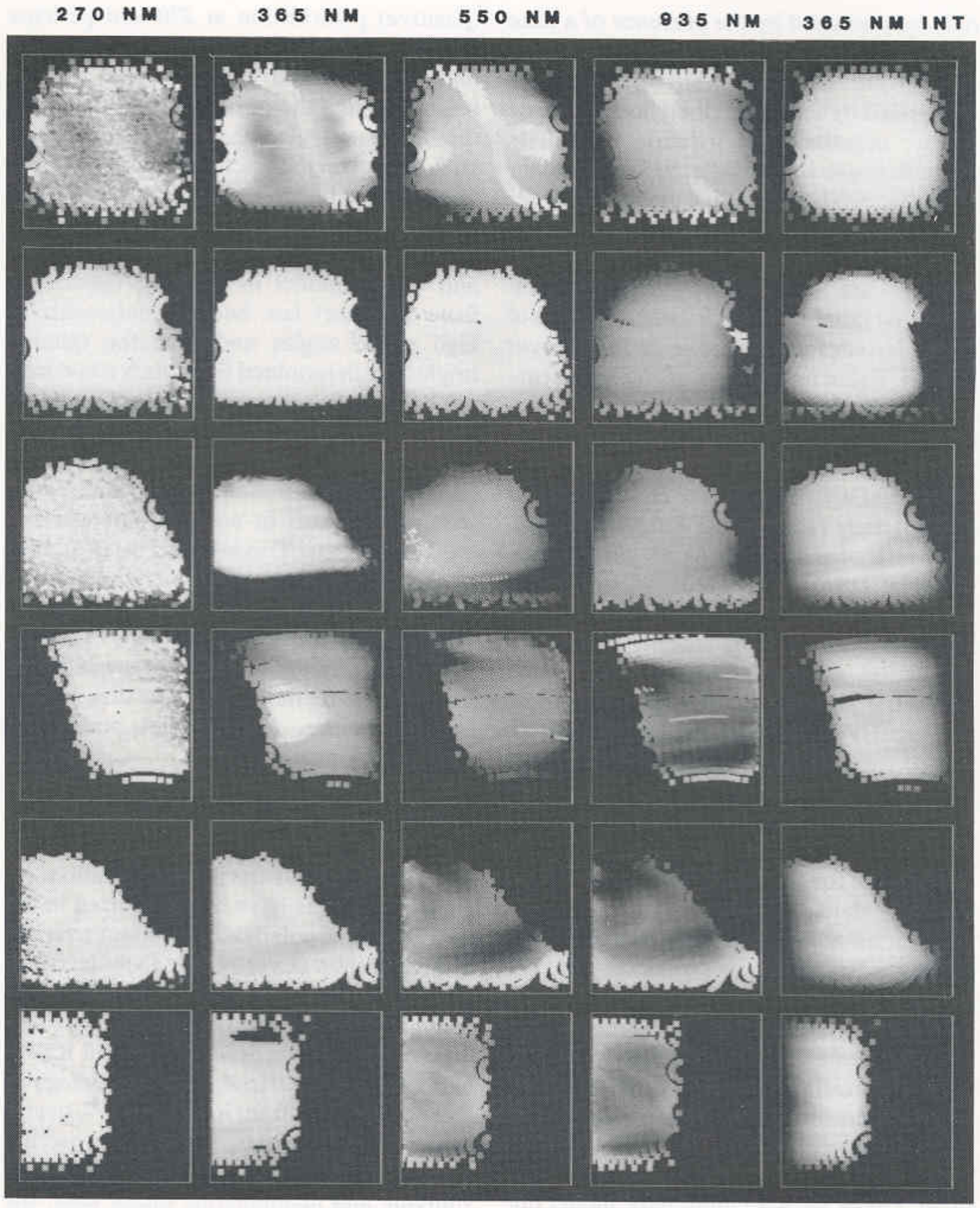


FIG. 8. Examples of structure in the polarization data at 270, 365, 550, and 935 nm. The maps are arranged by wavelength in vertical columns and in rows by phase angle (every 15°). The rightmost column shows the total (unpolarized) intensity image at 365 nm corresponding to the polarization data for each map. Table Ia gives relevant information about the observations.

After a long interval, Venus atmosphere is about to be explored by two spacecraft missions in the near future, at long last exploiting the near infrared windows that allow us to peer into the deep Venus atmosphere on the night side. The MESSENGER mission on its journey towards Mercury will fly-past Venus twice (August 2006 and June 2007) and observing it once on the second fly-by, much like Mariner 10 fly-by of Venus in February 1974, but approaching from the day side. In November 2005, Venus Express was successfully launched by ESA to make an extensive survey of the Venus atmosphere from a polar orbit with far more capable instruments than carried to Venus by any previous spacecraft beginning after orbit insertion in April 2006. Instruments and experiments on Venus Express Venus - Monitoring Camera (VMC), the Visible and Infra Red Thermal Imaging Spectrometer (VIRTIS), the Planetary Fourier Spectrometer (PFS) and the Venus Radio Experiment (VeRA) are expected to provide us with more comprehensive set of atmospheric observations over

three and perhaps more Venus days. These observations are expected to provide clues to the rocesses that maintain the rapid retrograde circulation of the bulk of Venus atmosphere. Much of what we know about the circulation has come from tracking of entry probes, cloud tracking from orbiter and fly-by spacecraft imagery, radio occultations and even ground based Doppler spectroscopy. Due to inadequate temporal and spatial coverage, these observations have not been sufficient to understand the circulation mechanisms that control it.

Despite its proximity to the Earth, Venus is a difficult target to observe from ground based or biting telescopes due to its high brightness and proximity to the Sun. Recent advances in infrared imaging at 2-4 microns has enabled us to observe the night side emissions from Venus with greater spatial resolution than before, but the temporal coverage is still difficult to achieve such as that which would be obtained from Venus Express from its polar orbit. What we lack are systematic, global observations of the Venus atmosphere over an extended time to enable us to resolve the solar thermal tides, the large scale planetary waves and other gravity waves perhaps triggered by the surface topography in the near neutral atmosphere of Venus below

~ 40 km. These can then help us understand how the Venus atmosphere super rotates at the equatorial latitudes and has a peak angular momentum density approximately 15-20 km above the surface. We look forward to the new observations of Venus from the new probes to provide with better systematic observations of the deep global circulation.

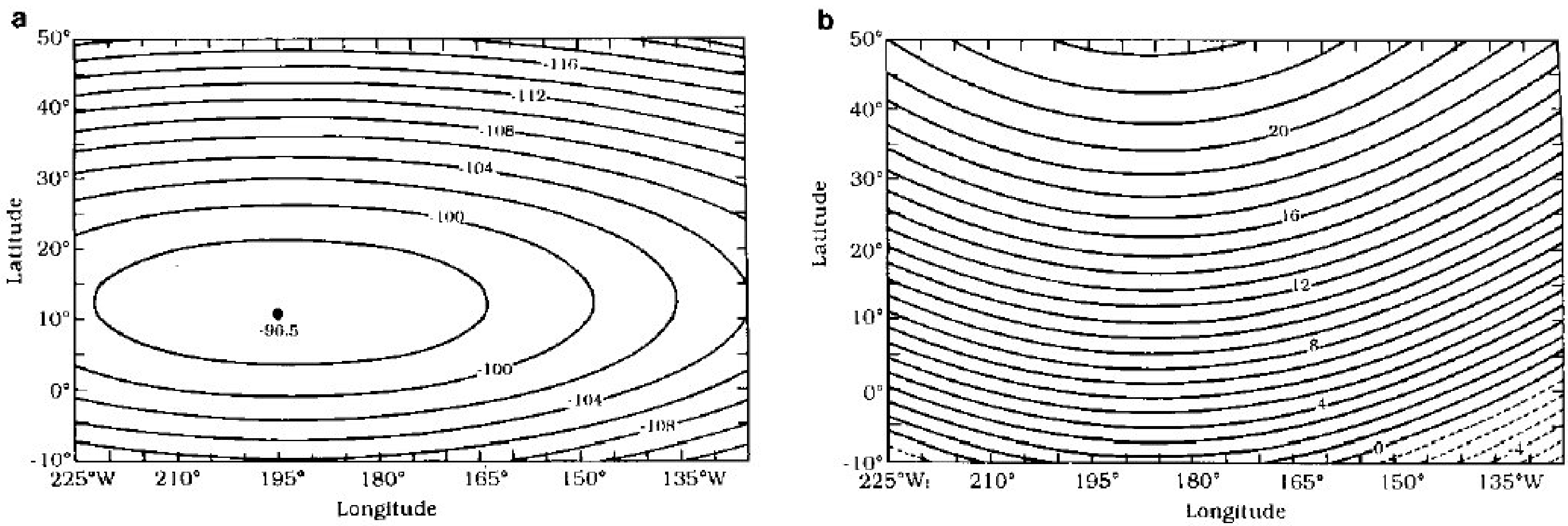


FIG. 5. Contour plots of a fit to the wind velocity obtained from the automatic feature tracker to the five lowest spherical harmonics. The zonal wind fit (Fig. 5a) is nearly flat giving weak jets at mid-latitudes. There also appears to be some divergence from a spot just north of the equator and in the afternoon. The meridional wind fit (Fig. 5b) shows poleward flow.

Why don't we know more?

- Insufficient observations of the global circulation of Venus over time and three-dimensional coverage
- Inadequacies of the current observations to answer some basic questions about the processes that should be important in maintaining the circulation

Ground Based Imaging Observations

- Boyer and Guerin first reported the 4-day wind from analysis of features in photographic images of Venus in 1961
- Polarimetric observations by Coffeen also showed evidence of atmospheric circulation
- Near IR imaging (Crisp, Meadows) has revealed lower atmosphere circulation

Spatial, Temporal coverage and resolution inadequate

Spectroscopic Observations

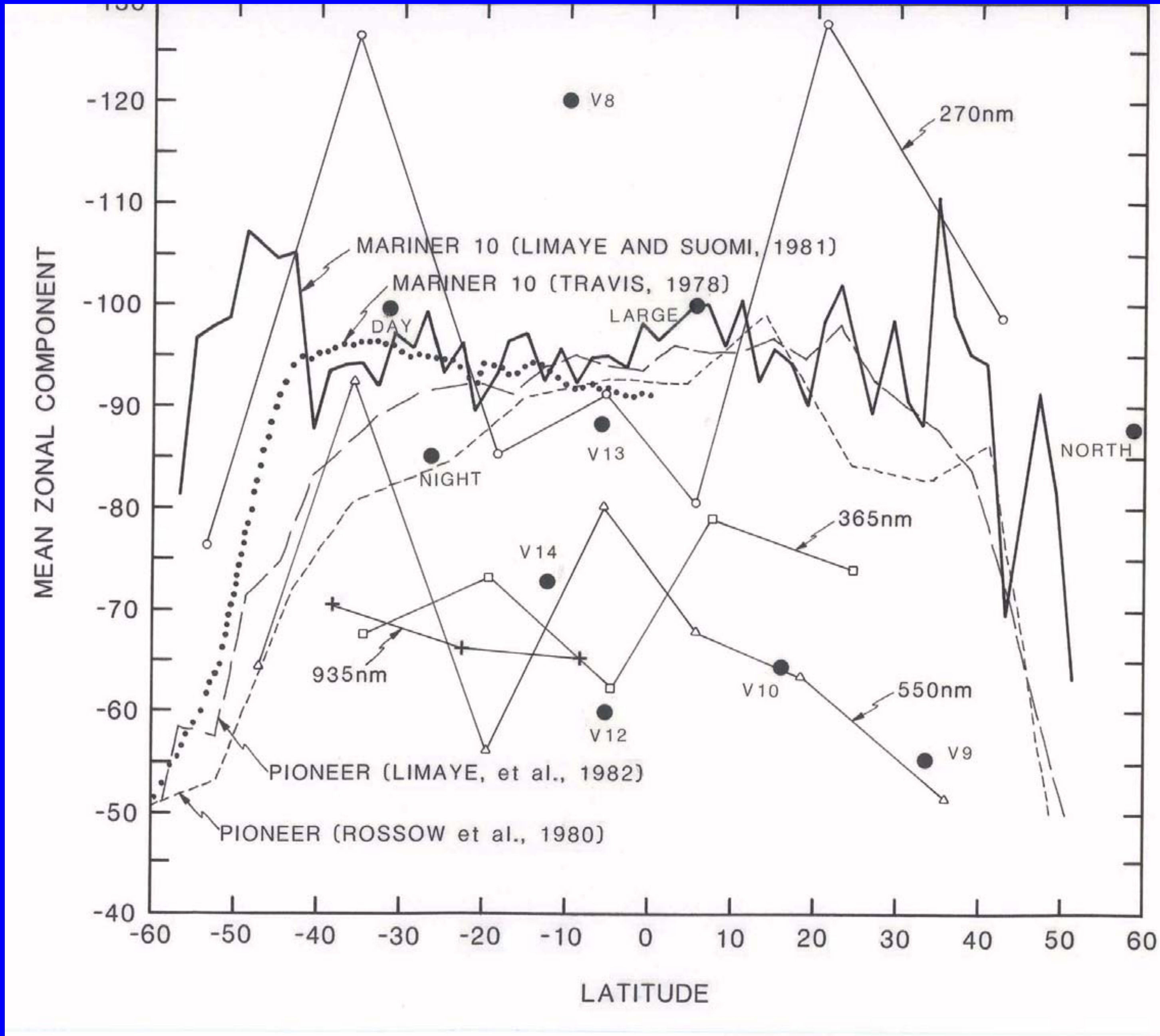
- Traub and Carleton obtained morning and evening limb visible observations in late 1960s
- 10μ measurements (Betz et al., Deming et al., Maillard et al., others)
- MilliMeter Wave observations Lellouch et al., Schloerb et al., Clancy and Muhleman, Goldstein

Measurements generally at near inferior conjunction. Temporal, Phase Angle coverage limited. Only obtain Line-Of-Sight component; limited vertical coverage

Earth Based Doppler Tracking of Entry Probe Signal

- Venera 4, 6, 8, 9, 10, 12, 13
- VeGa 1 and VeGa 2 Balloons
- Pioneer Venus Large Probe, 3 Small Probes

Lack of concurrent global circulation data at other levels, observations at different locations at different times of limited value in increasing our understanding



-120
-110
-100
-90
-80
-70
-60
-50
-40
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
MEAN ZONAL COMPONENT
LATITUDE
V8
270nm
MARINER 10 (LIMAYE AND SUOMI, 1981)
MARINER 10 (TRAVIS, 1978)
DAY
LARGE
NIGHT
V13
NORTH
365nm
V14
935nm
V10
550nm
V12
V9
PIONEER (LIMAYE, et al., 1982)
PIONEER (ROSSOW et al., 1980)

Map 1
t0

Map2
t0 + 4.5 hrs

Map 3
t0 + 9 hrs

Map 4
t0 + 13.5hrs

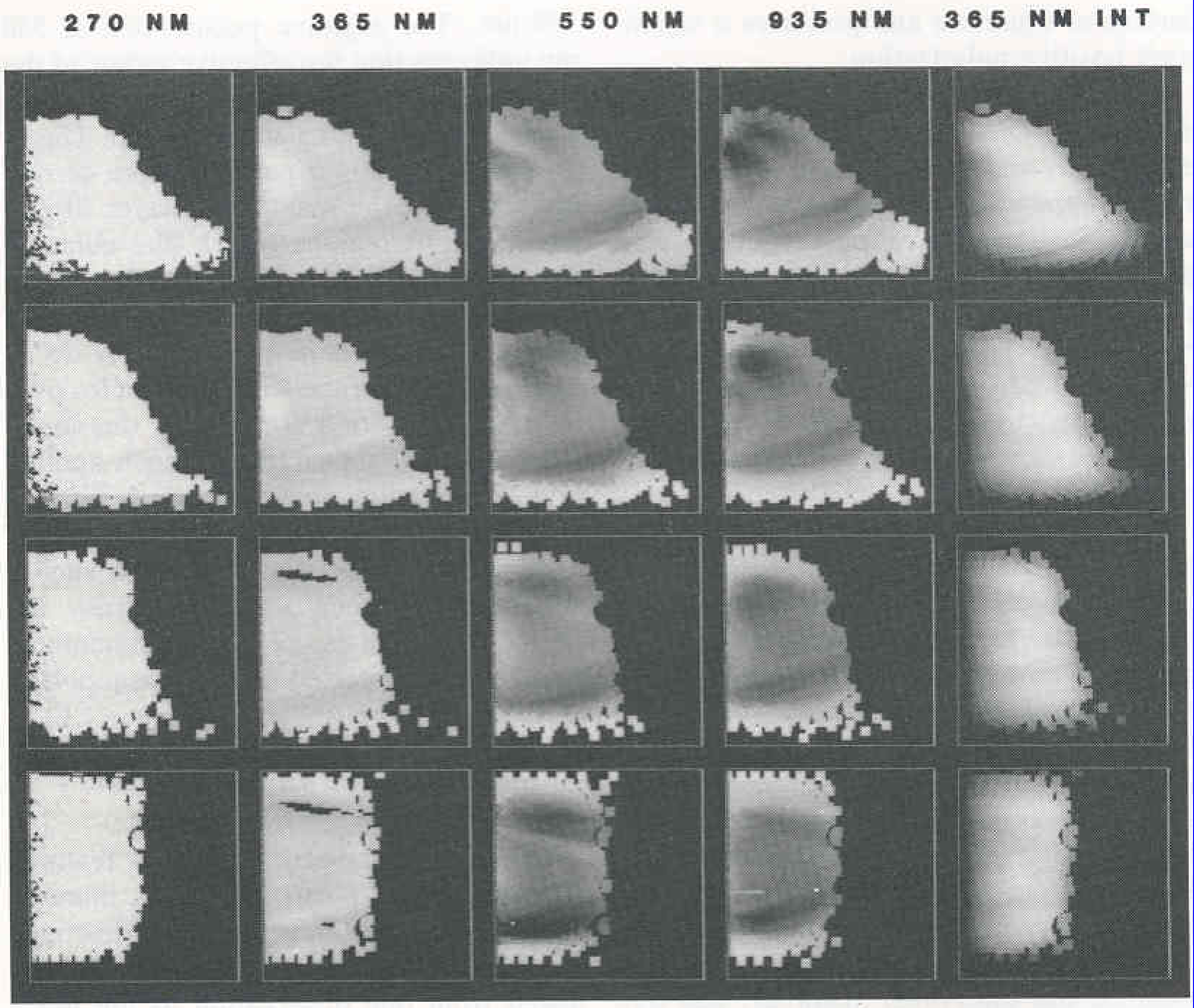


FIG. 9. Time series of polarimetry observations obtained on a orbits 336/337 (Table Ib). From left to right the images represent the 270, 365, 550 and 935 nm polarization amount (positive and negative, linearly scaled with 128 DN representing the 0% level), and the 365-nm intensity, all in rectangular projection. The first row represents the first observation in a sequence and subsequent observations are presented in successive rows. The nominal time interval between the first observation and the next one on the same orbit is between 4 and 5 hr.

Mid-Latitude Jets

- Pioneer Venus OCPP images suffered from low spatial resolution (~ 25 km) and low temporal sampling (~ 4.5 hrs typical) and hence the resulting cloud tracking missed the true strength of the mid-latitude jet that must have existed as inferred from the thermal structure data.
- VMC and VIRTIS will yield much higher temporal sampling of images with better spatial resolution and temporal sampling
- Pioneer Venus, Mariner 10 and Galileo results suggest variation in the strength of the jet on ~ months time scale