MEASURING WINDS ON VENUS AND OTHER PLANETS

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Abstract

The approach to measuring the circulation of the atmosphere of Venus was first attempted by following clouds in ground based images nearly five decades ago, even before the use of clouds to determine the atmospheric flow on Earth from geosynchronous weather satellite images. Mariner 10 images of Venus taken through an ultraviolet filter from television cameras in 1974 were the first spacecraft data to be used to estimate the global circulation of the atmosphere of Venus which also revealed the organization of the circulation in the form of two global scale vortices, one in each hemisphere centered over the respective poles. The basic technique was a minor adaption of the same software used to measure winds from Earth geosynchronous weather satellites developed at the Space Science and Engineering Center and used extensively in the Global Atlantic Tropical Experiment (GATE). Since then, the basic technique of cloud tracking to observe the global atmospheric circulation has been used extensively on Jupiter, Saturn, Uranus and Neptune. Variations of the same cloud tracking method have been used with considerable success. The measured cloud-tracked winds have been confirmed by direct entry probes, balloons (Venus) as well as from estimates of thermal structure using the balance equation or the thermal wind equation. At present European Space Agency's Venus Express orbiter is returning images of Venus from ultraviolet (reflected solar light) to near infrared (emitted radiation from Venus on the night side) spectral range. These are being used to monitor the atmospheric circulation of the Venus atmosphere from ~ 55 km to 70 km level. In December 2010 Japan's Venus Climate Orbiter is expected to go into orbit around Venus carrying ultraviolet and infrared cameras to monitor Venus from a near equatorial, eccentric orbit with a period that will give an approximate synchronous view of the Venus cloud cover over about 75% of the orbit, much like the view of Earth from geosynchronous weather satellite. Tracking of clouds from the returned images will provide vital data towards solving the puzzle of the super rotation of the Venus atmosphere.

Introduction

Understanding the weather and climate on other planets has become possible once the conditions in other planetary atmospheres became possible to be measured with instrumented probes, both remotely and landed or entry probes. Planets with atmospheres provide a natural laboratory to understand how physical conditions control weather and climate. The goal of determining meridional transports of momentum, energy and trace species in the Lorenz framework however remains a distant goal, although attempts are being made for Jupiter and Venus. Similarly general circulation models have also been developed or adapted for Mars, Venus and Jupiter. 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?

However, attempts to learn about the atmospheres of other planets began soon after first telescopic observations by Galileo when he discovered the phases of Venus and the Great Red Spot. Indeed, the first measurements of "winds" on a planet were obtained at Jupiter from drawings made from telescopic observations in the nineteenth century. These occurred long after Galileo first aimed the telescope at Jupiter and discovered the moons in the early seventeenth century. Observers noticed that many spots seen at different latitudes on Jupiter were long lived and appeared to move long latitude lines. By measuring the transit times, the period of rotation was measured and led to the discovery that the period for different latitudes was different. Until the rotation rate of the planet was measured from the radio emissions from Jupiter, the wind speed could not be determined precisely.

Just about the time of the birth of the space age, the photographic imaging of Venus was being done with ultraviolet and polarization filters and led to the discovery of the 4-day rotation rate of the

atmosphere. Only after the measurement of the rotation rate of the underlying planet did it become obvious that the clouds imaged moved more than fifty times faster than the rotation rate of the underlying surface. This contradicted the expectation that Venus would have day-night circulation based on the meager knowledge of the planet as late as 1950s.

On 14 December 1962, Mariner 2 became the first spacecraft to make observations another planet leading to a discovery of the high surface temperature of Venus (~ 750K) and cool cloud top temperatures. In less than five years later, while ATS-1 was launched on 7 Dec 1966 became the first geosynchronous Earth weather satellite on 18 October 1967, Venera 4 entry probe made the first successful measurements of the atmosphere of Venus, leading to the discovery of the high atmospheric pressure on the surface of the most earth-like planet. Figure 1 shows photographs of these early achievements.

Figure 1. From the left: Mariner 2 spacecraft, Venera 4 bus with the entry probe at the bottom, Venera 4 probe showing the bridle and transmitter, and Mariner 5 spacecraft.

Doppler tracking of the Venera 4 probe provided the first line-of-sight estimates of the winds in the atmosphere of Venus. Mariner 5 flew past Venus a day later, on 19 October 1967 and using the radio occultation technique for the first time, obtained the vertical profile of temperature in the thick atmosphere of Venus down to about 40 km. In 1974 Mariner 10 obtained the first detailed view of the Venus cloud cover using television cameras, followed by Pioneer Venus Orbiter (1978-1983) which used the multi color same spin-scan imaging method as used by ATS-3 and the early GOES spacecraft, and at present European Space Agency's Venus Express orbiter is providing images of Venus from ultraviolet to near infrared using CCD and infrared sensors (Figure 2).
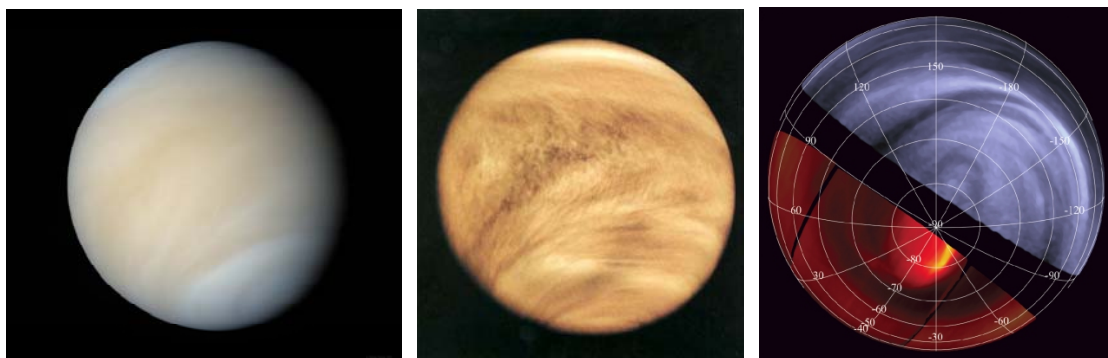

Figure 2. From left to right: Venus imaged in the ultraviolet light by cameras on Mariner 10 (February 1974), Pioneer Venus (using spin scan imaging) and more recently from Venus Express spacecraft from the VIRTIS instrument in near infrared (lower half of the image) and reflected ultraviolet (upper half of the image).

Besides exploring the moon and Venus, the nascent space exploration efforts were also successful at Mars (Mariner 6 and Mariner 9) and eventually in exploring the outer planets, beginning with Pioneer 10 to Jupiter and Pioneer 11 which went on to Saturn after a fly-by of Jupiter. Unlike the three-axis

Mariner spacecraft, Pioneers were spin-stabilized and carried the same spin-scan imaging system developed by Suomi and Parent for the ATS-1 geosynchronous satellite that revolutionized the weather observations of Earth as the technique was adopted by the Europe (METEOSAT) and Japan (Himawari) satellites.

The first images of the surface of another planet were taken by Venera 9 lander on October 22, 1975 while the mother spacecraft became the first spacecraft to orbit another planet. On 20 July 1976 Viking 1 landed on Mars and Viking 2 landed on to became the first two long lived surface meteorological stations in 1976 on another planet.

Pioneer 10 was the first spacecraft to make remote observations of the clouds of Jupiter in 1973, with closest approach on December 3rd. Its companion spacecraft Pioneer 11 also flew-past Jupiter in August 1974 and later encountered Saturn on 1 September 1979 to become the first spacecraft to return data on the clouds. Both Jupiter and Saturn have since been explored in greater depth by Voyager 1 and Voyager 2 spacecraft and by Galileo (Jupiter) and Cassini (Saturn) orbiters. Entry probe measurements in the outer solar system have been obtained by the Galileo probe entry into Jupiter (February 1994) and into Titan's atmosphere, the largest moon of Saturn in January 2001.

Figure 3. Jupiter images from Pioneer 10 and Cassini spacecraft and Saturn from Pioneer 11 and from Cassini orbiter. Pioneer 10 and images were obtained using the same spin scan imaging approach used by ATS-1, ATS-3 and the early GOES, METEOSAT and GMS geosynchronous satellites, except that the cross-scan coverage was obtained using orbital motion of the spacecraft instead of changing the telescope "look" angle. The Cassini images of Jupiter and Saturn were made using CCD cameras with 12-bit digitization, whereas the Pioneer images had much less dynamic range (6-bits digitization). The improved imaging capability has helped tracking clouds significantly.
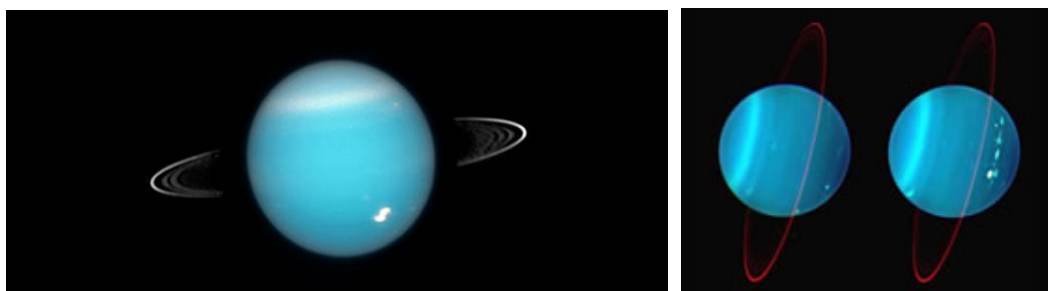

Figure 4. Uranus (left) and Neptune (right) imaged from Hubble Space Telescope and from Earth-based Keck telescope respectively. As seen from Earth, the angular sizes of these planets are only about 2.5 seconds or arc!

Only Voyager 1 and 2 spacecraft have explored the atmospheres of Uranus and Neptune up close although observations from Hubble Space Telescope and the modern Earth based observatories (NASA's Infrared Telescope Facility (IRTF) and the Keck Telescope and others) have provided excellent infrared observations of all the outer planets using adaptive optics enabling detailed measurements of the cloud level circulation.

Beyond the solar system, the advances in detecting planets around other stars are now enabling investigations of both terrestrial and Jovian planets and atmospheres. However, observations of winds and other meteorological parameters will be possible further in the future.

Diversity of Planetary conditions and circulations

The planets in our solar system exhibit diverse orbital and physical conditions (Table 1) and as a result the atmospheres (Table 2) they bear also show a range of meteorological conditions. Jupiter and Venus have only small or no seasonal variations, Mars, Saturn and Neptune and Pluto have discernable seasonal cycles. Uranus and Pluto have extremely long seasons due to their large inclination angle and seasonal effects have now been observed for the first time since their discovery in the last decade.

Table 1. Planetary conditions and orbital properties

Planet	Avg Distance in Million Km	Avg Distance relative to earth (AU)	Albedo	Radiative Eq. Temp.	Observed T (K)	Length of Year (years)	Length of Day (days)	Inclination of Rotation Axis (Deg.)	Eccentricity of Orbit
Mercury	57.6	0.39	0.12	436.0	200 – 800	0.241	58.65	2.0	0.206
Venus	107.4	0.72	0.76	230.8	750	0.615	243.01	177.3	0.007
Earth	148.6	1.00	0.32	254.4	288	1	1	23.5	0.017
Mars	226.4	1.52	0.25	211.3	220	1.881	1.029	25.2	0.093
Jupiter	773.4	5.20	0.34	110.7	144	11.862	0.411	3.1	0.048
Saturn	1418.7	9.54	0.34	81.7	85	29.458	0.428	26.7	0.056
Titan	1418.7	9.54	0.3	83.0	115	29.458	15.95	26.7	
Uranus	2852.3	19.19	0.3	58.5	60	84.01	0.748	97.9	0.046
Neptune	4470.9	30.08	0.29	46.9	58	164.79	0.802	29.6	0.01
Pluto	5865.8	39.46	0.4	39.3	40	248.54	6.387	122.5	0.248

We have now observed meteorological and geological processes as experienced on Earth, despite the different conditions. We have seen dust devils on Mars, vortex circulations on Venus, Jupiter and Saturn, extra-tropical cyclones on Mars, lightning on Jupiter and Saturn and measured electrical activity similar to that associated with lightning on Venus although optical detection has not yet been possible. Even precipitation has been inferred on Titan (methane) which also has the distinction of having lakes of liquid methane and other organic compounds on the surface. Water oceans underneath icy crusts are also inferred on moons of Jupiter (Ganymede and Europa) and Enceladus (a moon of Saturn) with frequent geyser displays.

One general pattern that has been observed is that the giant planets with atmospheres of hydrogen and helium have faster rotation rates compared to Earth and have primarily zonal circulations. Jupiter and Saturn show many easterly and westerly jets but Uranus and Neptune exhibit a different circulation regime with only one westerly jet in each hemisphere. One aspect common to atmospheric circulations of Venus, Jupiter, Saturn and Neptune is equatorial superrotation that is also seen in the upper atmosphere of Earth.

Making global observations of weather on planets is desirable to understand the workings of the respective atmospheres, but difficult to achieve in practice. Limited weather observations from the surface of another planet have been achieved on Venus, Mars and Titan (e.g. temperature, pressure, wind from anemometers and wind direction from wind socks, and even infrared interferometer on Mars). Only Mars has had sustained weather observations on the surface from landers such as Viking 1 (September 3, 1976 April 11 1980) Viking II (July 20, 1976 November 13, 1982), Sagan Memorial Station (Mars Pathfinder, 4 July 1996 - September 27, 1997) and Phoenix Lander (25 May 2008 – 30 October 2008). Missions to establish a surface network of weather stations continue to be studied and proposed and will eventually succeed in the future.

Measuring Winds on Planets

Until the dawn of the space exploration, the remoteness of the planets limited the measurement of winds on planets to earth based telescopes using visual observations (transit observations and drawings) in the 19th century and later photographic and later CCD imaging. While optical

spectroscopy was used for the measurement of the velocities of stars and galaxies by measuring Doppler shift of spectral lines, it was not applied for planetary wind measurements until the second half of 20th century (Traub and Carleton, 1975). At present Doppler spectroscopic measurements are being obtained at sub-millimeter wavelengths (Clancy et al., 2006; Widemann et al., 2008). Direct measurement of winds is possible only occasionally on the planets and vertical profiles can be obtained only with entry probes with interferometric tracking from Earth as has been done successfully for Venus, Jupiter and Titan. Another useful but less quantitative method is the use of surface features such as wind streaks and dunes to estimate the wind persistence, general magnitude and direction for Venus, Mars and Titan.

Table 2. Properties of planetary atmospheres in our solar system.

Planet	Acc. due to Gravity	Atmos. Composition	Eq. Radius (km)	Polar Radius (km)	Surface Pressure (bar)	Surface Temperature (K)	Major Cloud Composition	Cloud Top Temp	Max Winds (m/s)
Venus	887	96% CO_2, 4% N_2	6051.8	6051.8	90	750	75% H_2SO_4, 1 μ radius particles	220	140
Earth	980	N_2, O_2	6378.1	6356	1	300	H_2O liquid and ice phase	230	50
Mars	3.71	95.3% CO_2, 2.7% N_2 1.6% Ar	3396.2	3376.2	0.006	186 – 268	Frozen CO_2 and water ice	200	40
Jupiter	24.79	H_2, He	71400	66400	N/A	N/A	NH_3	144	170
Saturn	10.44	H_2, He	60000	56000	N/A	N/A	NH_3	120	450
Titan		N_2, CH_4	2575.5	2560	1.5		CH_4	100	150
Uranus	8.87	83% H_2, 15%He	25559	24973	N/A	76 (1 bar)	CH_4 NH_3	53 (0.1 bar)	100
Neptune	11.15	80%H_2, 19%He	24764	24341	N/A	72 (1 bar)	NH_3, CH_4	55 (0.1 bar)	200
Pluto	0.88	CH_4	1151		10^{-9}				

Cloud tracking on Planets
Cloud tracking was used first for Jupiter and Saturn well before the dawn of the space age, as early as 19th century to measure atmospheric jets or "currents" on Jupiter (Peek, 1958; Rogers, 1995) and Saturn, long before cloud tracking was used to determine winds in Earth's atmosphere from geosynchronous satellites. Cloud tracking is now being routinely used to determine the circulations of all planets with atmospheres from Venus to Neptune. Mars has been an exception until recently has the emphasis of most spacecraft exploring Mars has been surface geological investigations and thus imaging coverage has not been optimum for clout tracking. The Mars Global Surveyor and Mars Reconnaissance Orbiter are providing imaging coverage similar to that obtained from AVHRR and MODIS for Earth, and it is now becoming possible to measure cloud motions on Mars in polar latitudes. As with the Earth experience, determining the vertical level of the cloud motions remains a challenge on most planets.

Many aspects of cloud tracking on Venus and other planets are similar to tracking clouds on Earth and some of the same cloud tracking methods can be and have been used for planets while some techniques used for planetary winds may have use for earth applications, such as the particle velocimetry approach that has been used with considerable success with images of Jupiter (Read, 2005; Asay-Davis et al., 2009).

Some variations of cloud tracking, i.e. the process of determining a cloud feature's position in two different images acquired with an appropriate time interval have been used for planetary applications:

- Visual tracking – manual selection of a cloud feature in the first image followed by its visual identification (location) in one or two following images taken at appropriate time interval commensurate with the image resolution to keep the tracking error low compared to the expected wind.
- Computer augmented visual tracking – as above but using pattern matching methods (e.g. minimum absolute deviation, cross correlation, etc.) to determine the cloud feature location in the second image using a small target size (e.g. 24 x 24 image pixels)
- Automated digital tracking – the original target feature selection (e.g. 24 x 24 pixels) and its subsequent identification in the second image is done using a prescribed systematic approach to cover the image coverage area.

As on Earth, the first measurements of winds via cloud tracking were obtained through the visual identification and soon supplanted by computer augmented approach. One approach used is to use least squares approach if a feature can be tracked in more than three images as has been done quite successfully for Neptune (Limaye and Sromovsky, 1991) and Venus to a limited extent.   Lately automated tracking is being used extensively for Jupiter and to some extent Saturn, but its application to Venus is still problematic.
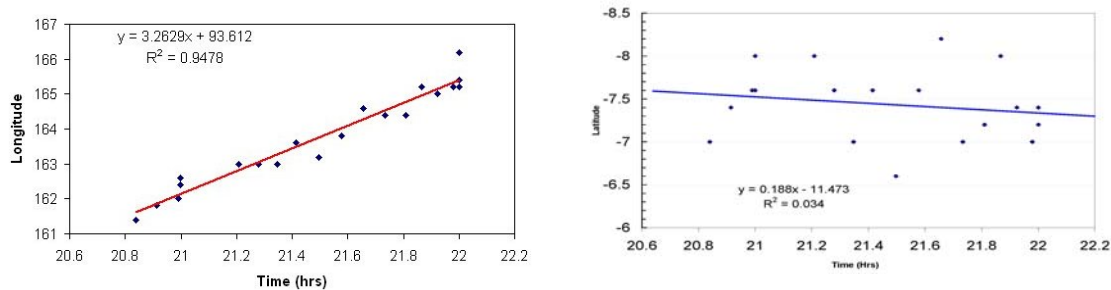

Figure. 5. Examples of estimates of zonal and meridional components of the cloud drift rate in a rapid imaging sequence obtained from the Venus Monitoring Camera on Venus Express orbiter, acquiring 20 images over a little more than one hour, allowing a least squares approach yielding an assumed constant drift rate in longitude and longitude. This approach has been particularly useful at Neptune where the clouds can dissipate quickly and a longer sequence improves the confidence in the drift estimates. *Given the low magnitude of the v-component, the larger scatter and hence error is apparent corresponding to the relatively low spatial resolution of the images and the short time interval.*

Wind Vector Quality Control
Determining cloud motions on other planets from images of the cloud cover are prone to the same errors as for the Earth – image navigation error and tracking error due to uncertainty in identifying the cloud position in the second image due to cloud evolution, image geometry and spatial resolution and illumination changes. The image navigation error in planetary images arises from lack of landmarks to verify the camera pointing on all planets except Mars due to the global cloud cover, particularly in the early space missions before the reliance on gyroscopic control of the pointing of the spacecraft.

Beyond the navigation and tracking errors, the main remaining challenge is validation of the results. In most cases the automated approach yields many false positives, i.e. vectors which yield implausible winds and thus the resulting winds need to be subjected to a quality control step. For Earth, one of the early metrics applied for geosynchronous satellite images was the use of image triplets taken 30 minutes apart with the requirement that the pair of vectors obtained from the first two images be "consistent" with the one obtained from the second pair. In the case of Earth, the availability of weather forecast models are a distinct advantage as they provide a guidance field for comparing the measured cloud motions with the forecast as a quality control tool. This is not yet feasible for the planets although forecast models for Mars are now maturing. Use of such models may be possible to some degree for Mars and even Venus if proposed missions to those planets being conceived or planned materialize to provide concurrent atmospheric observations.

Measurement of Cloud Motions on Jupiter

The tradition of measuring the drift rates of the spots on Jupiter is presently continuing with the amateur community providing most of the observations from small telescopes but equipped with digital cameras. Figure 4 shows some examples of color drawings and amateur images from which the drift rate of the spots can be determined. Indeed, with advanced image processing methods, the quality of the amateur images now surpasses the images obtained by professional observatories two or three decades ago. While modern large telescopes can match the detail of the far encounter images of Jupiter obtained from Cassini and New Horizons, the larger telescopes are not available for planetary observations for continued monitoring, thus the contributions of amateur observers are very valuable.
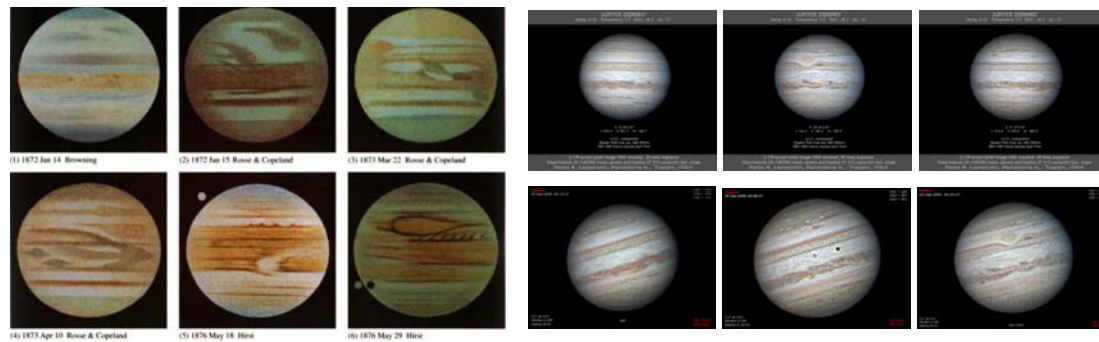

Figure 6.   Color drawings of Jupiter (Rogers, 1995) made from telescope observations used to determine the drift rate of spots (left) and a sampling of recent images of Jupiter from amateur astronomers from color CCD cameras and subsequent processing to bring out detail.

The drift rate measurements by using spot locations over several days is limited to obtaining zonal winds on a large scale. It requires long lived features to get meaningful measurements since the drift rates are ~ tens m/s.   Winds over smaller spatial scale and shorter time interval have been obtained from Voyager (Limaye et al., 1982) and Cassini images of Jupiter (Vasavada and Showman, 2005). Although the meridional component was resolved, the measurement accuracy is lower compared to the zonal component. Nevertheless, Del Genio et al. (2007) report estimates of eddy momentum transport from the zonal and meridional components.

Determining Zonal Mean Zonal Flow from longitudinal brightness distribution from global maps

The 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. With a short rotation period, it is possible to make a global mosaic of Jupiter quickly, even from ground based images.
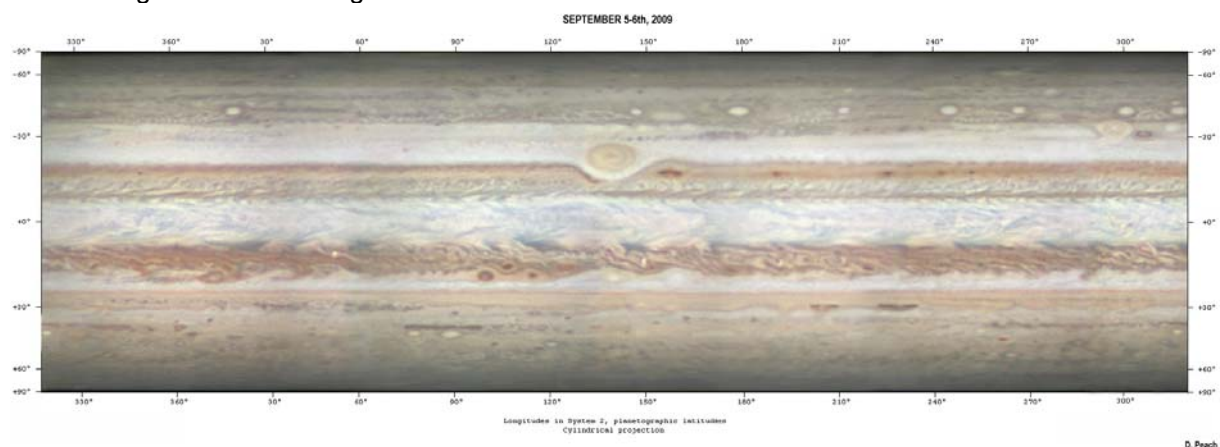

Figure 7. An example of the state of the art quality of amateur imaging of Jupiter. The global map was produced by Damian Peach from images taken during 5-6 September 2009.
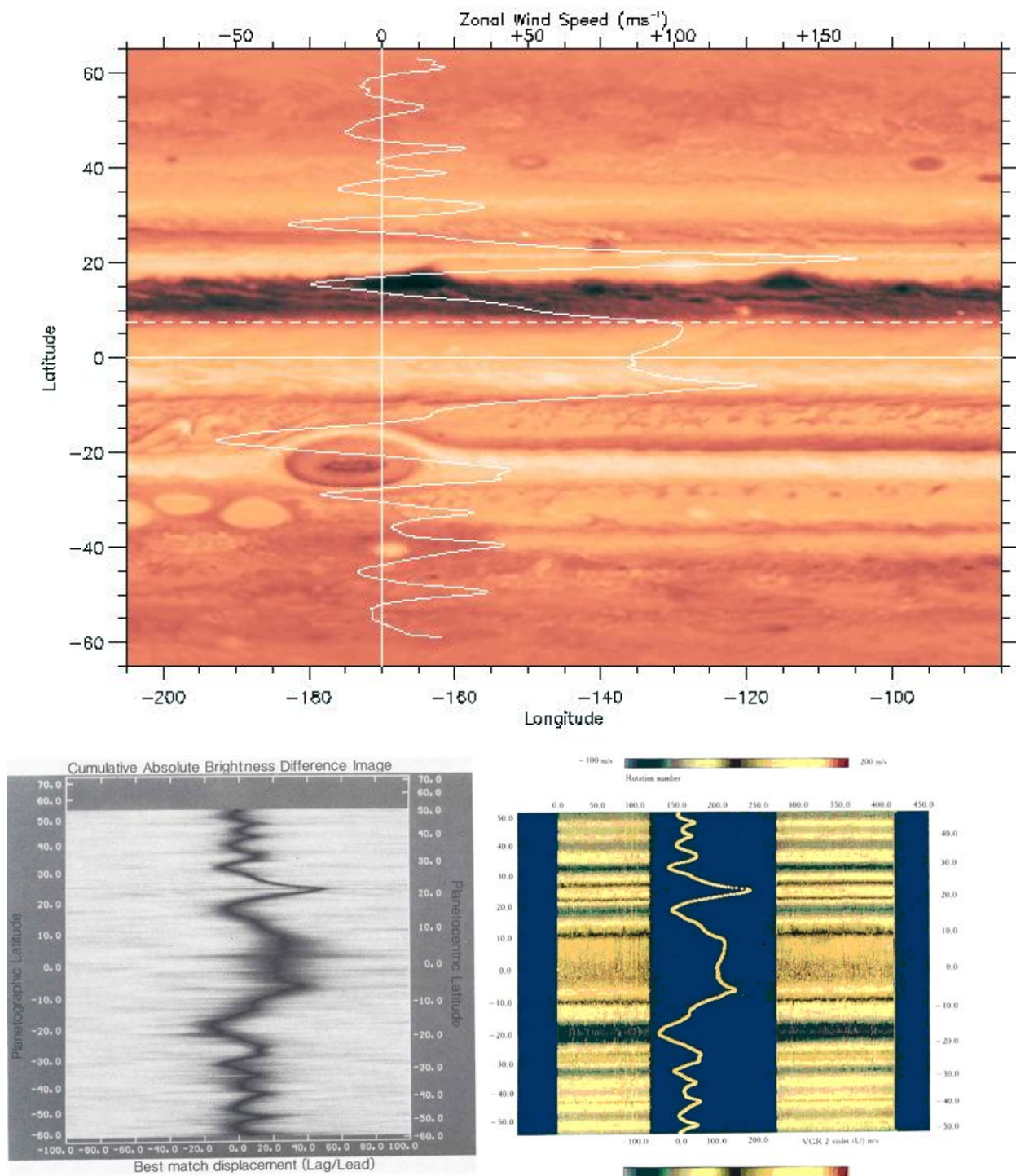
Figure 8. The zonal average zonal flow (top) on Jupiter (Limaye, 1986) obtained from global maps generated for every rotation from violet filter images taken by Voyager spacecraft with an accuracy of less than 2 ms⁻¹. The approach used minimum absolute deviation as the pattern matching metric (lower left) as it is less prone to noise compared to cross correlation and is able to yield reliable rotation by rotation estimates of the average zonal flow enabling studies of the temporal evolution of the zonal flow (lower right).

The zonal average tracking method works well for Jupiter and Saturn (Limaye, 1989), but the disadvantage is that the map resolutions used do not enable a useful determination of the average meridional flow which on Jupiter and Saturn is one to two orders of magnitude smaller than the peak

jet magnitudes. The larger meridional flow on Venus, the presence of surface features on Mars and lack of availability of global maps every rotation for Uranus and Neptune hinder the use of the zonal tracking method for determining the average flows on those planets.

Advection Particle Velocimetry Approach to Fine Scale Determination of the Flow from Images
A new approach for measuring winds on Jupiter uses an iterative approach using particle velocimetry (Read et al., 1995; Asay-Davis et al. 2009) in which an estimate of the flow is compared with the cloud morphology and using the difference between the observed morphology and advected version from the wind estimate to refine the wind measurement successively until the difference is small. This approach has yielded very impressive results for Jupiter. This method is computationally quite intensive but may be very useful in obtaining better results from water vapor imagery from the weather satellites.

Measuring Winds on Venus
First spacecraft image based measurements of cloud motions and the global circulation were obtained from Mariner 10 television images (Suomi, 1975). 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, Venus exhibits an elegant vortex circulation (Suomi and Limaye, 1978; Limaye et al., 2009) with superrotating winds at the cloud level (Limaye and Suomi, 1981). At present European Space Agency's Venus Express orbiter is returning images at 365, 513, 935 and 1010 nm wavelengths. Since Venus shows most contrast at ultraviolet wavelengths, 365 nm images are being used to determined cloud motions from images with spatial resolution ranging from about 45 to 25 km/pixel. Figure 8 shows results obtained from cloud tracking from two image triplets acquired on a single day with one hour interval between the images. Tracking results over many days are being used to detect the presence of solar thermal tides and other planetary scale waves. Another goal is to estimate the meridional transport of angular momentum by the zonal mean and eddy circulation at the level of the ultraviolet clouds, which has been now determined to vary from about 73 km to 67 km altitude between the equator and the south pole.
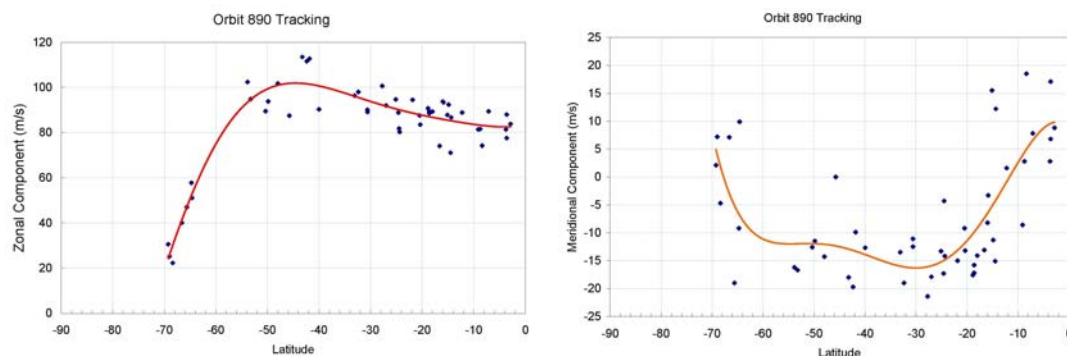

Figure 9. Cloud tracking results from ultraviolet images from the Venus Monitoring Camera on Venus Express orbiter, taken on orbit 890.

Cloud Tracking on Mars

Images from the MARCI experiment on Mars Reconnaissance Orbiter are being used to determine cloud motions on Mars at high latitudes by using the overlap of the images obtained on successive orbits in the polar region, similar to the MODIS and AVHRR coverage in Earth's polar regions (Santek et al., 2009). The availability of surface features has helped reduce the navigation errors due to poor pointing knowledge and improve the measured winds by using their known locations of selected surface features.
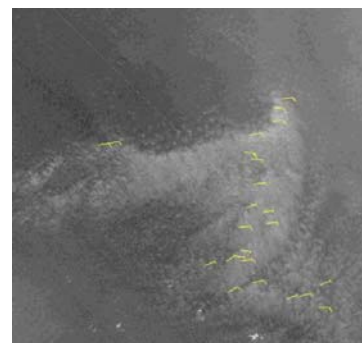

Figure 10. An example of cloud motions derived from overlapping images of Mars from MARCI using the same McIDAS cloud tracking package used for GOES/POES data.

Tracking clods on Uranus and Neptune

Voyager 2 spacecraft obtained images of Uranus in 1986 and of Neptune in 1989 during the respective fly-bys. Uranus images showed only seven distinct clouds whose motions were measured. In contrast, Neptune showed many more clouds and their motions were measured using multiple images (Limaye and Sromovsky, 1991). Subsequently ground based images from NASA's Infrared Telescope Facility (IRTF) and the Keck telescope as well as multispectral images obtained from the Hubble Space telescope have been used to detect changes in the atmospheric circulations of Uranus and Neptune from cloud motions.

Of all the solar system planets and moons with significant atmospheres, only Titan remains an anomaly by being the only object where discrete cloud tracking has yet to be successfully applied.

Summary

Spacecraft and telescopic observations of planetary atmospheres are being used to learn about their atmospheric circulations. Cloud tracking is one of the more practical tools to learn more about the global circulations of the planetary atmospheres. Numerical modeling efforts have been undertaken to understand the planetary circulations(e.g. Lebonnois et al., 2010) many being adaptions of Earth General Circulation Models (Richardson et el., 2007) such has NCAR's Community Atmosphere Model (CAM) More work is needed in improving the determination of cloud heights in other planetary atmospheres to obtain better vertical structure information. Multispectral imaging and images taken in polarized light have been found to be useful in cloud level determination on Venus and Jupiter, but more data and analysis are needed. Temporal, spatial and spectral coverage are essential to learning more about these circulations and provide answers to the questions regarding the structure of the planetary atmospheric circulations and how they evolve and are maintained. Some of the questions include the following:

- How are equatorial "super-rotations" seen on Venus, Jupiter and Saturn produced and maintained?
- What determines a planet's atmospheric circulation regime?
- What is the role of the rotation rate of a planet and the number of jets on planets?
- What distinguishes the jet structures on Saturn and Jupiter from those on Uranus and *Neptune?*

There are other many questions regarding the planetary atmospheres which provide the basis for exploration efforts in order to improve our understanding, particularly as comparative to Earh's weather and climate evolution and our ability to predict future states. The gaps in our ability are illustrated by the inability to realistically simulate the circulations of the slowly rotating planets such as Venus and Titan.

There is a wealth of data being accumulated and a greater engagement by the terrestrial atmospheric community in exploring the planetary atmospheres will prove to be quite useful. The first planetary atmospheres symposium was held at the 90th Annual meeting of the American Meteorological Society in Atlanta, Georgia in January 2010, and it is hoped that other such opportunities will follow.

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