Two years of Saturn's exploration by the Cassini spacecraft: atmospheric studies

Agustín Sánchez-Lavega, Ricardo Hueso and Santiago Pérez-Hoyos

Grupo Ciencias Planetarias, Dpto. Física Aplicada I, Universidad del País Vasco
agustin.sanchez@ehu.es

1 Introduction

Jupiter and Saturn are giant gaseous planets similar in their size, rotation rate and averaged physical and chemical properties. Both have a rich meteorology at the upper cloud level (pressures from a few mbar to about 3 bar) as observed in the visible and thermal infrared wavelength ranges (wavelengths 200 nm to 5 μm), and in the stratosphere and upper troposphere as sensed in the thermal infrared (wavelengths 7.8 - 50 μm) and using radio occultation methods. Atmospheric observations by Cassini spacecraft cover all this spectral range being performed with a variety of instruments. The "Imaging Science Subsystem" (ISS) is a two camera system formed by a narrow angle telescope (2 m focal, 0.35° FOV) and a wide angle telescope (0.2 m focal, 3.5° FOV), both using CCD detectors (1024 square array of pixels), and a large set of filters (wide and narrow) ranging from UV (264 nm) to near IR (1012 nm)[1]. The "Visual Infrared Mapping Spectrometer" (VIMS) is a multi-channel spectrometer which simultaneously acquires 352 bandpasses ranging from 0.35 to 5.1 μm, with two separated channels: visual (CCD detector) and near-IR (single element detector) [2]. The "Composite Infrared Spectrometer" (CIRS) consists of two Fourier-transform spectrometers covering the wavelength range 7 μm - 1 mm at a high resolving power [3]. The "Radio and Wave Plasma Science" (RPWS) experiment is designed to measure the electromagnetic radio emissions from 1 Hz to 16 MHz able to detect radio bursts from lightning activity and to extract the vertical temperature profiles from radio occultation investigations [4].

Cassini atmospheric studies focus on several topics. A major unresolved puzzle in these atmospheres is the nature of the system of zonal jet winds alternating in the East-West direction with latitude. A particular mystery is the mechanism giving raise to the broad and intense equatorial jets on both planets [5, 6]. Globally Jupiter's jets are stable in time in their peak latitude location and intensity within about ten per cent, but little is known about the temporal stability of Saturn's jet system. Another important subject of research is the nature of the meteorological phenomena that are observed in the stratosphere and upper troposphere (vortices, waves and convective storms). The vertical and latitudinal structure mechanisms that form the hazes and clouds, the origin of the chromophore agent that gives the color to the clouds, and the temperature maps and the chemical distribution of non homogeneous compounds are other scientific objectives in the atmospheric studies of Saturn.

2 Saturn meteorology

Saturn's upper troposphere is expected to contain three main cloud layers according to thermochemical modelling [7] and radio observations [8, 9]. They are composed of ammonia (pressure level P $\sim$ 1 - 1.4 bar), ammonium hydrosulfide (NH_4SH, P $\sim$ 2-4 bar) and water (P $\sim$ 8-10 bar). Above the ammonia cloud, thick hazes extend up to few mbars. Radiative transfer modelling in the visible wavelengths allows to retrieve the upper cloud structure [10, 11, 12]. Most atmospheric features seen at visual wavelengths locate above the 1 bar level, and somewhere between 2-4 bar those sensed in the infrared window at $\sim 5\mu$m.

2.1 Temperature and composition

The temperature and chemical composition of the lower stratosphere and upper troposphere are being analyzed by the CIRS instrument and to some extent by the RPWS in the radio occultation mode. On the one hand, the meridional gradient of the stratospheric temperatures so far measured from 0.1 mbar to 0.5 bar imply a strong decay of the equatorial winds with altitude and a warm south polar stratosphere, as expected from seasonal insolation changes [13]. The temperature data also suggest vertical motions (upwelling in bands and downwelling in belts), with intense upwelling at equator. On the other hand, the spatial variations of PH_3 and para-H_2 indicate overturning motions in the troposphere (Hadley-like), and the NH_3 distribution suggests different spatial levels of condensation [14]. The elemental abundances measurements indicate that C and P are both enriched but N is depleted with respect to protosolar values [14]. The C/H ratio is seven times solar, twice that of Jupiter.

2.2 Dynamical phenomena

Vortices

Saturn closed vortices have an oval shape and low albedo contrast as first shown by Voyager 1 and 2, and most have anticyclonic vorticity [15, 16, 17]. The Cassini ISS images show also vortices in different latitudes of the northern hemisphere (fig. 1) [18, 19], some of them merging after their close encounter.

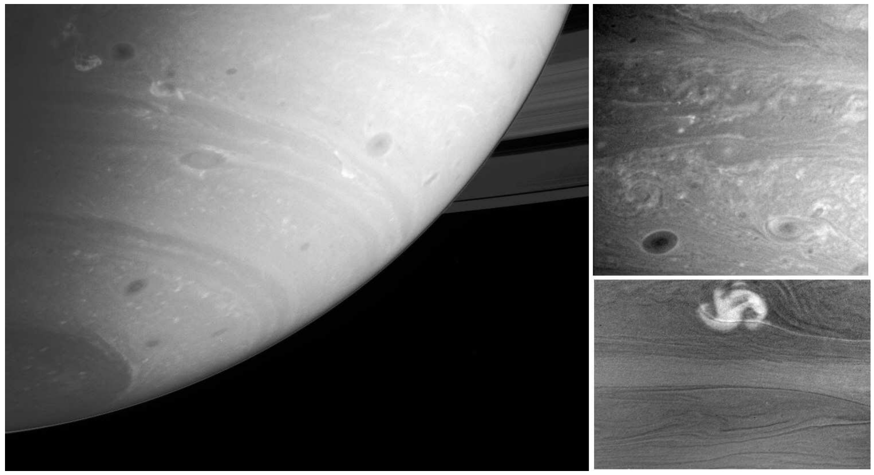

Fig. 1. Examples of Saturn's meteorological phenomena captured with Cassini ISS: Vortices and bright clouds (left: PIA 06507 on Sept. 19, 2004, filter CB2; lower right: PIA 07564 on July 6, 2005, filter CB2), and a convective storm with associated burst radio emission (lower right: PIA 07789 on January 27, 2006, filter CB2).

They seem to be ubiquitous since they were detected as spots in HST images [20]. Much work remains to be done on the measurement of their properties (wind field, temperature and chemistry).

Convective storms

Bright, irregular in shape, mid-scale clouds that evolve rapidly, were also common in the Voyager era at mid-latitudes and in the equatorial area, referred here as "plumes" [15, 16, 17, 23]. They are usually interpreted as the result of wet convection on the ammonia or water clouds [24]. The most dramatic convective events are the rare "Great White Spots" (GWS) that are large-scale phenomena disturbing completely the zone where they emerge. The most recent events occurred in 1990 [25] and 1994-95 [26] at Equatorial latitudes, between the Voyagers and Cassini visits. The ISS images show a continuous activity of several smaller storms at mid northern latitudes (fig. 1), and radio emissions episodes (Saturn electrostatic discharges, SED) associated to lightning in these storms have been detected by the RPWS [18, 27, 28]

Waves at cloud level

During the Voyager encounters two distinct waves covering the full circumference (latitude circle) were detected at cloud level: the so-called "ribbon" at mid-northern latitudes [17] and the "hexagon" close to the north pole [21] (fig. 2), re-observed later using the HST and ground-based facilities [29, 30].

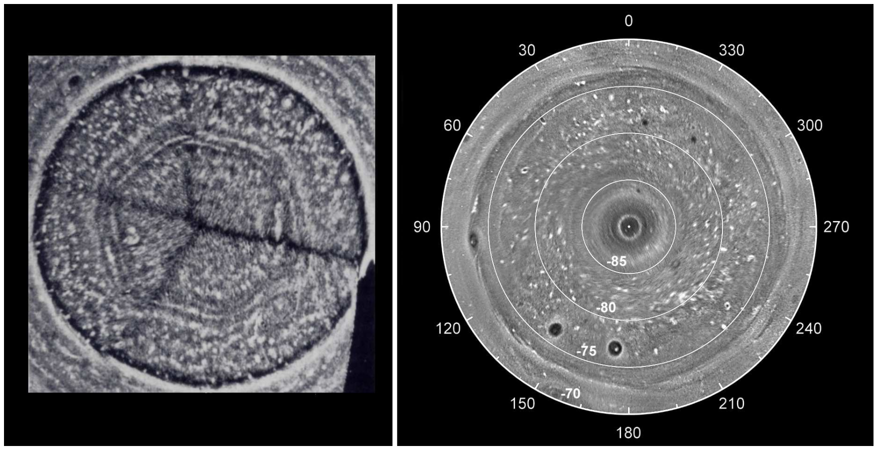

Fig. 2. Left: Saturn's North Polar Region showing the hexagonal wave at the time of Voyager 2 (1979) [21]. Right: Saturn's South Pole in a map composed Cassini ISS CB2 images [22].

Therefore they are long-lived waves and potential targets for Cassini ISS. Their nature is not yet well established although it has been proposed that they are Rossby waves evolving in a sheared flow [31, 32]. Other less prominent waves were seen in a reanalysis of the Voyagers southern hemisphere images [23], and some waves, extending along short latitude sectors, are evident in Cassini images.

The first released images and results using VIMS are strongly promising in retrieving the meteorological phenomena and winds in the mid-altitude cloud (NH_4SH), as never seen before (fig. 3) [33, 34].

3 Winds and circulation

Saturn has a broad and intense zonal jet extending between latitudes $\pm 40°$ blowing eastward with maximum speed at cloud level of 475 ms^{-1} as measured during the Voyagers encounters in 1980-81 [35, 23]. The jet showed much lower speeds during 1996-2004 [36, 20] and vertical wind shears were proposed to explain the velocity differences [18]. However, a new analysis of Saturn's cloud vertical structure during the Voyager encounters suggested that real changes have occurred in the jet at cloud level [37]. Distinguishing between dynamical variability (temporal changes) and permanent vertical wind shears or the existence of both, is a fundamental step to understand the mechanisms and energy sources, external (solar) or internal (deep convection), that intervene in creating this strong jet. It must be mentioned that the velocities are measured relative to the System III reference frame determined by the radio rotation period (assumed to be tied to the deep interior) as measured by the Voyagers

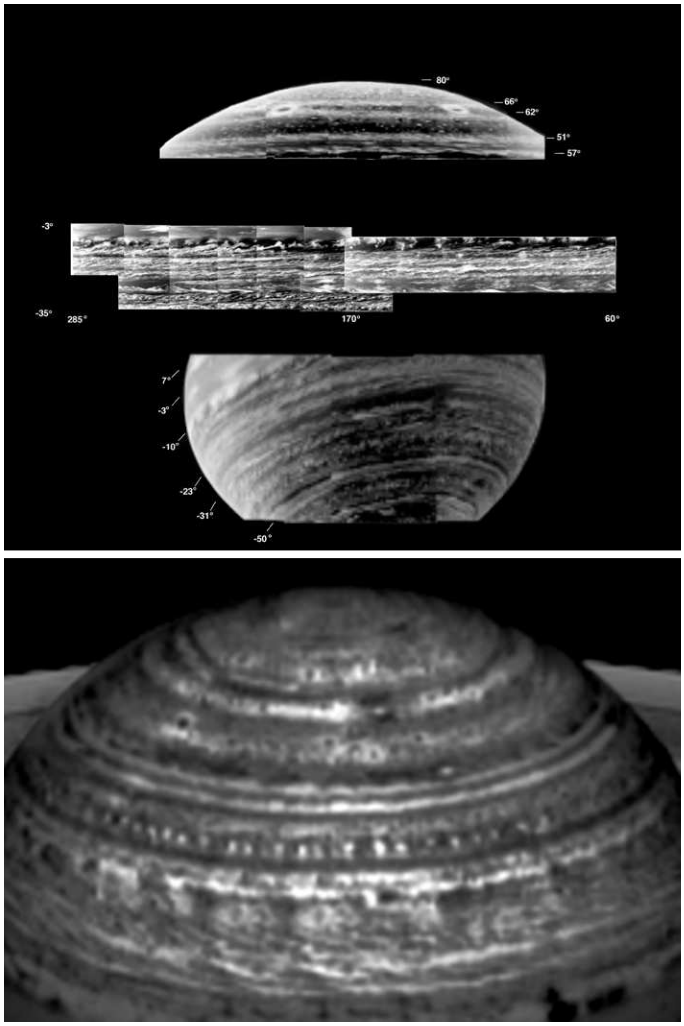

Fig. 3. Images of the deep cloud layer observed at ~ 5 μm with VIMS. The top image was acquired on Feb. 17, 2005, the second image on March 8, 2005, and the third on July 12, 2005. The lower image (PIA 01941) was acquired on April 27, 2006.

[38]. However Ulysses and Cassini measurements of radio emission recurrence and, in this last case, of the magnetic field rotation, show variability in this period by at least several minutes, so it remains to be determined what is the Saturn rotation period [39].

The ISS camera is taking images of the planet regularly since 2003, but in particular since April 2004, before orbit injection. The images allow to track the atmospheric features motions [18, 19, 22, 40] (see fig. 2) and when prop-

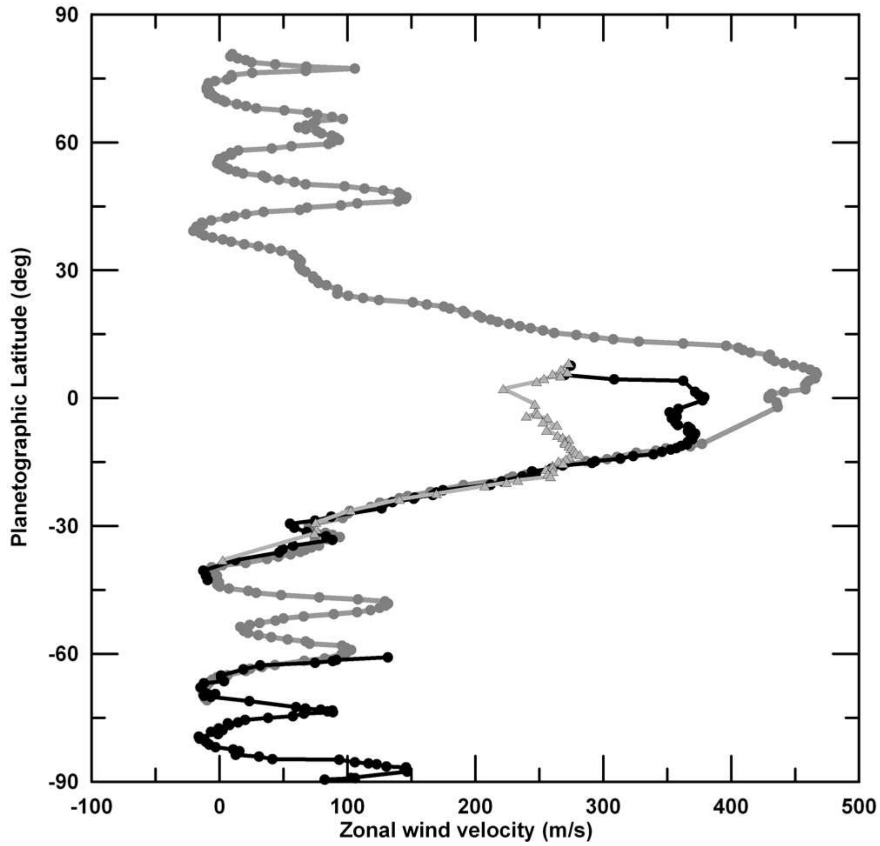

Fig. 4. Saturn's zonal wind profile from two missions: grey line and dots from Voyager 1 and 2 in 1980-81 [23]; grey line with triangles and black line with dots from Cassini ISS images in 2004-05 [22, 40]. Note the profile differences at equator.

erly calibrated in intensity, to infer the upper cloud and haze vertical structure using radiative transfer models [22, 40]. The first published study of motions in Saturn's atmosphere using ISS images [18] showed two distinct patterns of zonal wind velocities at southern Equatorial latitudes based on the tracking of about 40 features in two filters: (a) The methane band MT2 (727 nm) sensed higher altitudes and detected low speeds; (b) The CB2 continuum filter (750 nm) sensed lower altitudes and detected higher speeds. These results are in agreement with the vertical wind shears derived above the clouds from temperature measurements and application of the thermal wind relationship [13]. We have extended this study increasing the temporal base, the wavelength coverage and the number of targets. Our results show that between latitudes 5°N and 12°S the winds increase their velocity with depth from 265 ms^{-1} at the 50 mbar pressure level to 365 ms^{-1} at 700 mbar. These values are below the high wind speeds of 475 ms^{-1} measured at these latitudes during the Voyager era in 1980-81, indicating that the equatorial jet has suffered a significant intensity change between that period and 1996-2005 or that the tracers of the flow used in the Voyager images were rooted at deeper levels than those in Cassini images (fig. 4). Other works studied the motions at non Equatorial latitudes [19], mainly the temperate latitudes, where the winds showed good agreement with Voyager 1 and 2 (1980-81) and our HST data (1996-2004). One important result we have obtained analyzing Cassini ISS images was the discovery of a very strong vortex encircled by an intense jet with maximum speeds of 160 ms^{-1} at the south pole ([22]; fig. 2 and 4).

4 Future prospects

Ongoing analysis and future additional images and measurements with the battery of atmospheric Cassini instruments should give precise information on the 3D temperature structure, aerosol properties and their vertical distribution, and chemical abundances and distributions of the different species (including aerosols) in both hemispheres, as well as their temporal variability. Cloud motions from the near infrared imaging with VIMS in the 4-5 micron window, with deeper penetration than in the visible, and the determination of the precise altitude location of the tracers at these wavelengths will complete the full 3D structure of the winds in Saturn's upper troposphere.

Acknowledgments: This work has been supported by the Plan Nacional de Astronoma y Astrofsica (MEC) AYA 2003-03216 and Grupos UPV 15946/2004. R. Hueso was supported by the Ramón y Cajal Program (MEC). This research made use of the public Cassini images available at NASA Planetary Data System.

References

1. C.C. Porco et al.: Space Sci. Rev. **115**, 363 (2004)
2. Brown, R. A. et al.: Space Sci. Rev., **115**, 111 (2004)
3. F.M. Flasar et al.: Space Sci. Rev. **115**, 169 (2004)
4. D.A. Gurnett et al.: Space Sci. Rev. **114**, 395 (2004)
5. A.P. Ingersoll, T.E. Dowling, P.J. Gierasch, G.S. Orton, P.L. Read, A. Sánchez-Lavega, A.P. Showman, A.A. Simon-Miller, A.R. Vasavada: Dynamics of Jupiter's Atmosphere. In *Jupiter: The Planet, Satellites & Magnetosphere* (Cambridge University Press, Cambridge, MA. 2004) pp 105–128
6. A.R. Vasavada, A.P. Showman: Rep. Progr. Phys. **68**, 1935 (2005)
7. S.J. Weidenschilling, J.S. Lewis: Icarus **20**, 465 (1974)
8. F.H. Briggs, P.D. Sackett: Icarus **80**, 77 (1989)
9. A.W. Grossman, D.O. Muhleman, G.L. Berge: Science **245**, 1211 (1989)

10. M.G. Tomasko, R.A. R.A. West, G.S. Orton, V.G. Tejfel: Cloud and aerosols in Saturn's atmosphere. In: *Venus*, (University of Arizona Press, Tucson, Arizona 1984) pp 150–194
11. E. Karkoschka, M.G. Tomasko: Icarus **106**, 428 (1993)
12. S. Pérez-Hoyos, A. Sánchez-Lavega, R.G. French, J.F. Rojas: Icarus **176**, 155 (2005)
13. F.M. Flasar et al.: Science **307**, 1247 (2005)
14. L.N. Fletcher, P.G.J. Irwin, N. Teanby, G.S. Orton, P.D. Parrish, R. de Kok, S.B. Calcutt, C. Howett, P.L. Read, F.W. Taylor and the Cassini/CIRS Team: Bull. Amer. Astron. Soc. **38**, 501 (2006)
15. B.A. Smith et al.: Science **212**, 163 (1981)
16. B.A. Smith et al.: Science **215**, 504 (1982)
17. L.A. Sromovsky, H.E. Revercomb, R.J. Krauss, V.E. Suomi: J. Geophys. Res. **88**, 8650 (1983)
18. C.C. Porco et al.: Science **307**, 1243 (2005)
19. A.R. Vasavada, S.M. Hrst, M.R. Kennedy, A.P. Ingersoll, C.C. Porco, A.D. Del Genio, R.A. West: J. Geophys. Res. **111** (2006)
20. A. Sánchez-Lavega, R. Hueso, S. Pérez-Hoyos, J.F. Rojas, R.G. French: Icarus **170**, 519 (2004)
21. D.A. Godfrey: Icarus **76**, 335 (1988)
22. A. Sánchez-Lavega, R. Hueso, S. Pérez-Hoyos, J.F. Rojas: Icarus **184**, 524 (2006)
23. A. Sánchez-Lavega, J.F. Rojas, P.V. Sada: Icarus **147**, 405 (2000)
24. R. Hueso, A. Sánchez-Lavega: Icarus **172**, 255 (2004)
25. A. Sánchez-Lavega, F. Colas, J. Lecacheux, P. Laques, I. Miyazaki, D. Parker: Nature **353**, 397 (1991)
26. A. Sánchez-Lavega, J. Lecacheux, J.M. Gomez, F. Colas, P. Laques, K. Noll, D. Gilmore, I. Miyazaki, D. and Parker: Science **271**, 631 (1996)
27. D.A. Gurnett et al.: Science **307**, 1255 (2005)
28. Fischer et al.: Icarus **183**, 135 (2006)
29. A. Sánchez Lavega: Icarus **158**, 272 (2002).
30. A. Sánchez-Lavega A., S. Pérez-Hoyos, J. R. Acarreta, R. French: Icarus **160**, 216 (2002)
31. M. Allison, D. A. Godfrey, R. F. Beebe: Science **247**, 1061 (1990)
32. D.A. Godfrey, V. Moore: Icarus **68**, 313 (1986)
33. K. Baines et al.: Earth Moon Plan. **96**, 119 (2005)
34. T.W. Momary et al.: Bull. Amer. Astron. Soc., **38**, 499 (2006)
35. A.P. Ingersoll, R.F. Beebe, B.J. Conrath, G.E. Hunt: Structure and dynamics of Saturn's atmosphere. In: *Saturn*, (University of Arizona Press, Tucson, Arizona 1984) pp 195–238
36. A. Sánchez-Lavega, S. Pérez-Hoyos, J.F. Rojas, R. Hueso, R.G. French: Nature **423**, 623(2003)
37. S. Pérez-Hoyos, A. Sánchez-Lavega: Icarus **180**, 161 (2006)
38. M.D. Desch, M.L. Kaiser: Geophys. Res. Lett.,**8**, 253 (1981)
39. A. Sánchez-Lavega: Science **307**, 1223 (2005)
40. A. Sánchez-Lavega, R. Hueso, S. Pérez-Hoyos: Icarus, in press (2007)