

## LONG-TERM VARIABILITY OF THE ZONAL WINDS OF JUPITER AND SATURN

A. Sánchez-Lavega<sup>1</sup>, R. Hueso<sup>1</sup>, S. Pérez-Hoyos<sup>1</sup>, E. García-Melendo<sup>2</sup>, and J. F. Rojas<sup>3</sup><sup>1</sup>Física Aplicada I, E.T.S. Ing. Universidad del País Vasco, Alda. Urquijo s/n, 48013, Bilbao, Spain.<sup>2</sup>Esteve Duran Observatory Foundation, Seva, Barcelona, Spain<sup>3</sup>Física Aplicada I, E.U.I.T.I., Universidad del País Vasco, Pza. La Casilla s/n, 48012, Bilbao, Spain.

## ABSTRACT

We describe the temporal variability of the zonal jets of Jupiter and Saturn from a long-term systematic observation of motions at the upper cloud level. Globally, the pattern is highly stable but significant changes on the strongest eastward jets of each planet have been detected. The first one is the speed variability in the 180 m/s jet stream in Jupiter's north temperate latitude. The second one is the change by about 40 percent in the speed of the equatorial jet of Saturn. We discuss the possible nature of these changes and how they can be used to constrain the models of the giant planets general circulation.

Key words: Planets: Jupiter – Planets: Saturn

## 1. INTRODUCTION

The aspect of Jupiter and Saturn at wavelengths ranging from the ultraviolet ( $\sim 200$  nm) to the near infrared ( $\sim 5$  microns), is dominated by the diffuse reflection of sunlight (scattering and absorption) by gases and solid particles (clouds and hazes) at pressure levels  $\sim 0.1 - 2$  bar. The tracking of individual cloud elements at these atmospheric levels along a given time interval, allows us to measure their motions relative to the rotation of the magnetic field, assumed to be that of the planet itself. Ground-based and spacecraft observations have revealed that the atmospheric circulation of Jupiter and Saturn is dominated by a system of zonal jets, i.e. winds directed along the parallels and alternating their direction East or West with latitude. There are about 8 and 4 eastward jets per hemisphere in Jupiter and Saturn respectively (see Figures 1A and 2A). A conspicuous characteristic of this pattern is the existence of a latitudinally broad eastward equatorial jet with peak velocities of  $\sim 150$  ms<sup>-1</sup> in Jupiter and  $\sim 475$  ms<sup>-1</sup> in Saturn (the velocities are taken positive for motions in the eastward direction). At present, there is no accepted theory to explain the nature of these motions and the models so far proposed are on a rudimentary stage (Ingersoll et al. 2004, Sánchez-Lavega et al. 2004a). The understanding of the general circulation of the giant planets represents a major theoretical challenge for a broad community formed by planetary scientists, astrophysicists and meteorologists and should be a major objective in the

future research of the Jovian planets. Some of the basic questions to be answered are: Which are the driving energy sources for these winds? How deep do they extend? How do these low thermal energy atmospheres generate the intense wind speeds? How did the broad and intense eastward equatorial jets form? Why Jupiter's westward jets keep stable violating known geophysical fluid stability criteria at the same time (Ingersoll et al. 1979, Li et al. 2004)?

## 2. ASSESSING THE GENERAL CIRCULATION

Let's first summarize the most remarkable physical aspects of the giant planets (Ingersoll et al. 2004): (1) They are fluid spheres with a size  $\sim 10$  times that of the Earth; (2) They have a high angular rotation velocity (rotation periods  $\sim 10$  hr); (3) They have a significant internal energy source, a factor  $\sim 1.7$  of the absorbed sunlight radiation; (4) Whereas the sunlight absorption depends strongly on the sub-solar latitude (due to the planetary axis tilt), the emitted energy is independent of it; (5) The solar energy available in Jupiter and Saturn is a factor  $\sim 1/25$  and  $1/100$  respectively of that received on the Earth. Paradoxically the winds are ten times stronger; (6) The atmospheres of the giants are deep, covering an important fraction of the planet radius, and frictionless when compared to the Earth since they lack a solid surface; (7) These planets are fully cloud covered; (8) Thermodynamic effects related to latent heat release from cloud condensation and from ortho to para conversion of molecular hydrogen, could have important influence on the global dynamics in the upper atmosphere; (9) The details of the internal structure and composition of these planets could have a significant role on the observed motions (e.g. magnetic and friction effects in the metallic-molecular transition region, or the existence of opacity sources influencing the heat transfer in the interior); (10) We do not know how energy is dissipated in these atmospheres; (11) We do not know either which is the role of the rich meteorology (convective storms, large-scale close vortices, waves) on the zonal circulation.

The general circulation models so far presented differ mainly on the dominant energy source driving the motions and consequently on their altitude extent below the clouds. There are two basic proposals: "deep" models, where the internal heat source is the basic energy

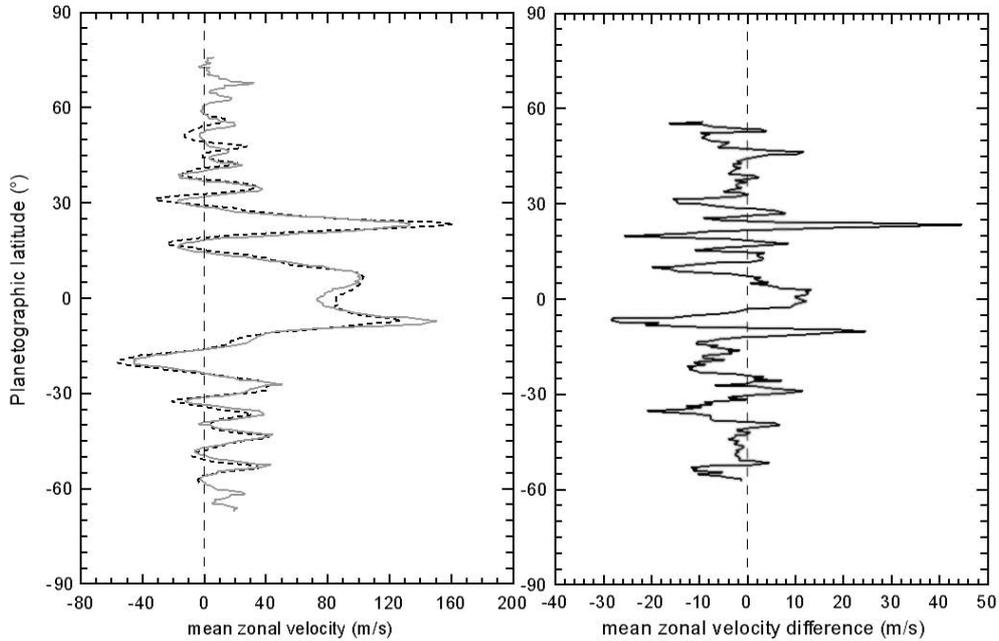


Figure 1. Variability of Jupiter winds. Left figure shows wind profiles measured in two different periods: Black dashed line, *Voyagers* (1978); Grey continuous line, *HST* (1996 to 2000). Right figure shows differences between both profiles.

mechanism with motions extending along the whole hydrogen molecular layer (up to pressure of  $\sim 1$  Mbar), and "shallow" layer models, that extend a few bars below the main upper cloud layer (down to 10-100 bar) and have the solar radiation and thermal to kinetic energy conversion as the main driving energy source (Ingersoll et al. 2004, Sánchez-Lavega et al. 2004a). There are several possibilities to distinguish between these two basic hypothesis: (1) The most obvious one is to measure the winds below clouds. Direct measurements of the winds were performed in Jupiter by the Galileo probe (Seiff et al. 1997). The data showed an increase of the winds below the ammonia cloud layer from  $105 \text{ ms}^{-1}$  at 0.5 bar to  $180 \text{ ms}^{-1}$  at 3 bar and then a value essentially constant down to 24 bar. The problem is that Galileo entered a peculiar meteorological region at 7.5 North, a "hot spot", and it is doubtful if the measured winds reflect local conditions or the general circulation (Showman and Dowling 2000). Multi-probes, at selected latitudes and able to reach the 100 bar level would be the best technique to attack this problem; (2) Another alternative is to measure, using a polar orbiting spacecraft with a low periape (1000 km above the atmosphere), the gravity anomalies that the rapid zonal jets produce if they involve enough mass (down to the 10 kbar level, equivalently 1000 km) (Hubbard et al. 1999, Guillot et al. 2004); (3) Other indirect determinations of the wind profile at deep levels are, in general, model dependent as, for example, those that used the circular waves detected

on some SL-9 impacts in 1994 (Dowling et al. 1995) or the studies of the dependence on the wind vertical structure from numerical simulations of particular atmospheric disturbances (García-Melendo et al. 2005); (4) The problem can be constrained studying the long-term variability of the jet pattern (i.e. latitude location of the jet peak, maximum speed, and meridional width and shape) at the scale of the planet year (11.85 years for Jupiter and 29.42 years for Saturn). The reason is that shallow layer models are more sensitive to the seasonal insolation changes and meteorology variability than deep layer models. Although the radiative time constant in the upper troposphere (pressure level 0.5 bar) is large in Jupiter (2-3 years) and Saturn (6 years), seasonal changes are expected due to the orbital eccentricity in the case of Jupiter (Beebe et al. 1986), and to the rotation axis tilt in the case of Saturn (Bèzard et al. 1984). In this last case, the effect is enhanced in the equatorial area because of the ring shadowing (Barnet et al. 1992a). On the contrary, deep layer models predict the jet pattern to be symmetric relative to the Equator, extending along the whole molecular hydrogen atmosphere from one hemisphere to the other. According to this hypothesis the winds are deep, therefore the mass involved should have an enormous inertia and make the jets very stable in time (Sánchez-Lavega et al. 2004a). In what follows we summarize the long-term measurements of the stability of zonal flows in Jupiter and Saturn and the implications for the nature of the circulation.

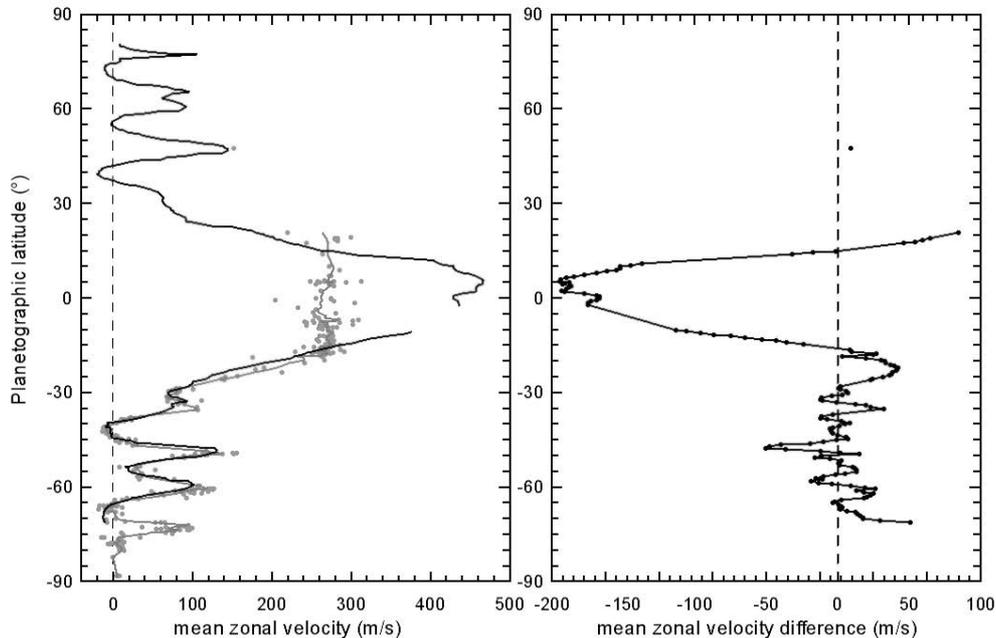


Figure 2. Variability of Saturn winds. Left figure shows wind profiles measured on two different periods: Black line, Voyagers (1981); Grey dots, individual measurements of cloud features on HST images (1996 to 2004); grey line is a fit to this data. Right figure shows differences between both profiles.

### 3. VARIABILITY OF JUPITER AND SATURN ZONAL FLOWS

Before the Voyagers spacecraft arrival, the systematic measurements of Jovian winds from low resolution, ground-based observations since 1850, suggested the winds to be in general stable (Peek et al. 1958, Smith and Hunt 1976, Rogers 1995). Global measurements very precise in speed (typically  $< 5 \text{ ms}^{-1}$ ) at high spatial resolution (100-200 km) were carried out from Voyager 1 and 2 images in 1979 (Limaye 1986), Hubble Space Telescope from 1996-2000 (García-Melendo & Sánchez-Lavega 2001) and the Cassini flyby in 2000 (Porco et al. 2003). The mean zonal wind profiles derived from such analysis are compared in figure 1. The data cover two Jupiter's years and confirm the stability inferred from old ground-based data. However, significant deviations in the profiles can be seen between the Voyager and Cassini-HST observation periods at particular latitudes (see Figures 1B and 2B). The most conspicuous are the changes the change in the peak velocity of the rapid jet at 23.5 N (from  $180 \text{ ms}^{-1}$  to  $140 \text{ ms}^{-1}$ ), and the peak and shape of the equatorial eastward jet (between 10 N and 10 S). According to our studies, the difference of  $40 \text{ ms}^{-1}$  in the strongest Jovian jet at 23.5 N was probably due to the outburst of a large convective event followed by a planetary-scale disturbance (García-Melendo et al. 2000, García-Melendo et al. 2005). This is the only case reported in Jupiter where a huge meteorological

phenomenon could have produced a change in the mean zonal wind. In the case of Saturn, ground-based data on the wind profile are scarce, and only about 12 single measurements were available from 1870 to 1990 (Sánchez-Lavega 1982). The 1981-82 flybys of Voyager 1 and 2 gave the first precise measurements of Saturn's wind profile (Ingersoll et al. 1984, Sánchez-Lavega et al. 2000). Later on, the development of the Great White Spot in 1990 (a huge storm) allowed us to gather new wind data at equatorial latitudes (Sánchez-Lavega et al. 1991, Barnett et al. 1992b). Although some changes were found, the most unexpected result was the detection of a large drop of about  $200 \text{ ms}^{-1}$  in the equatorial winds on HST images taken a few years later, between 1996 and 2004 (Sánchez-Lavega et al. 2003, Sánchez-Lavega et al. 2004b) (Figure 2A). The first high precision Cassini measurements in 2004, suggest that the change could not be real but related to a vertical wind shear effect (Porco et al. 2005). The subject is still under debate, but according to our most recent data, a real change between the Voyager and HST-Cassini era winds seems to have taken place in the upper troposphere (Pérez-Hoyos & Sánchez-Lavega 2005), perhaps related to the development of large-scale convective equatorial disturbances. On the other hand, at non-equatorial latitudes, all the data (ground-based, Voyager, HST and Cassini) suggest the winds to be highly stable in time.

## 4. CONCLUSIONS

The average long-term stability of Jupiter and Saturn wind profiles, with low sensitivity to insolation changes, points toward a "deep" origin for their zonal winds. The observed variability in some jets at cloud level in both planets seems to be related to the development of energetic meteorological phenomena, whose dynamically induced motions modify temporarily the zonal jets. Future advances in this topic will require new spacecraft observations at high resolution (50 km or less) with a high temporal sampling rate. Establishing the stability and turbulent momentum and energy transfer in Jupiter's atmosphere, and identifying the signature of the winds in the gravity field would give a high constraint to the models. For Saturn, we must await the completion of the Cassini mission to see if new light is added on this subject.

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