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**A strong decrease in Saturn's equatorial jet at cloud level**

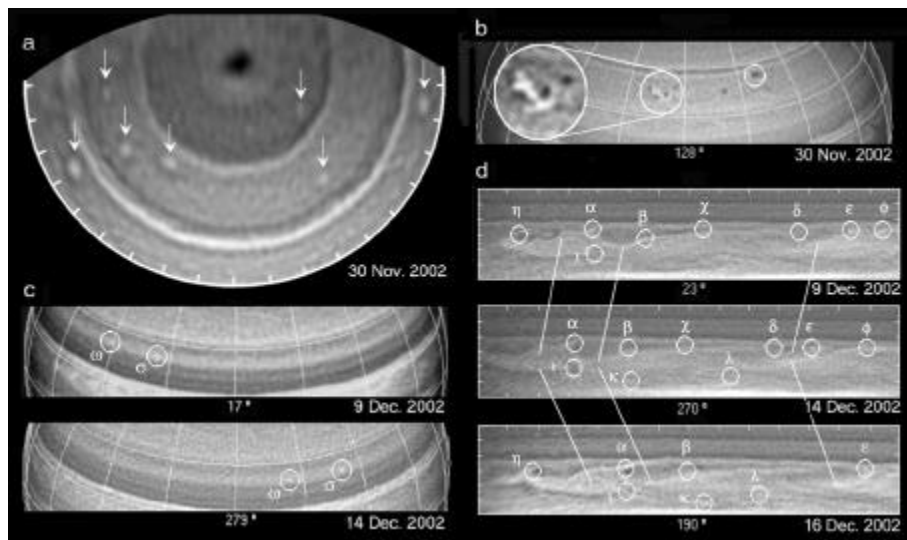
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The atmospheres of the giant planets Jupiter and Saturn have a puzzling system of zonal (east–west) winds alternating in latitude, with the broad and intense equatorial jets on Saturn having been observed previously to reach a velocity of about  $470 \text{ m s}^{-1}$  at cloud level<sup>1</sup>. Globally, the location and intensity of Jupiter's jets are stable in time to within about ten per cent<sup>2,3</sup>, but little is known about the stability of Saturn's jet system. The long-term behaviour of these winds is an important discriminator between models for giant-planet circulations<sup>4–9</sup>. Here we report that Saturn's winds show a large drop in the velocity of the equatorial jet of about  $200 \text{ m s}^{-1}$  from 1996 to 2002. By contrast, the other measured jets (primarily in the southern hemisphere) appear stable when compared to the Voyager wind profile of 1980–81.

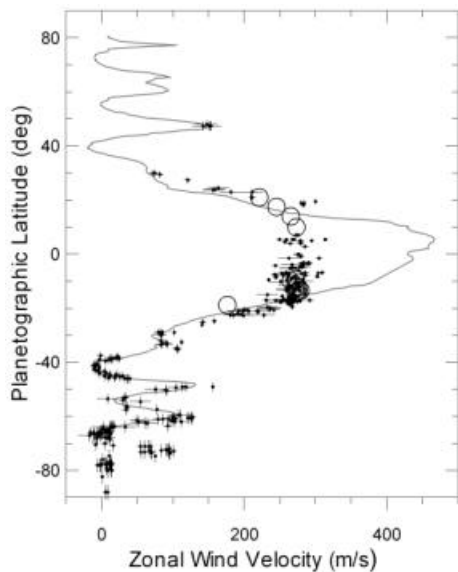
The first precise measurements of Saturn's zonal wind velocity profile were performed during the Voyager encounters in 1980–81 (refs 10, 11). Previous wind measurements, obtained by tracking individual 'spots' in the atmosphere, are scarce, but are in general agreement with the Voyager data<sup>12</sup>. Cloud motions measured on

Voyager images revealed a strong and broad equatorial jet (peak velocity  $\sim 470 \text{ m s}^{-1}$ , spanning planetographic latitudes  $\pm 40^\circ$ ), twice as broad and four times more intense than that of Jupiter. The equator is also the place where infrequent but violent eruptions (the 'Great White Spots') occur<sup>13–15</sup>. As Saturn has a large obliquity of  $26.7^\circ$ , and the shadow of the rings produces strong insolation changes in the equatorial region, induced effects during Saturn's year (29.4 terrestrial years) could be expected at cloud level where the winds are measured<sup>16</sup>. The zonal jet measurements rely on the detection and tracking of cloud features, and because of the lower contrast, size and number of such features in Saturn than in Jupiter, this can only be performed at present using the Hubble Space Telescope (HST). The Voyager data were obtained during the northern hemisphere spring (1980–81), and HST high-quality images of Saturn are available for the period 1994–2002, during Saturn's southern hemisphere spring and early summer. Both epochs are well placed to look for long-term changes. The HST images analysed here were obtained between 1996 and 2002 (3–6 days per year) using the Wide Field Planetary Camera 2 (WFPC2) at its maximum spatial resolution. A series of filters from 255 to 1,042 nm were used, including at times a filter isolating the 890-nm methane absorption band (dates and filters for each campaign are given in Supplementary Information). In total, about 100 images were selected, navigated on the planetary limb and photometrically calibrated. Images obtained at wavelengths of 439 nm, 675 nm, 814nm and 890 nm showed the clouds to have high contrast (enhanced by an 'unsharp masking' processing), and were used for target identification and tracking. Image pairs or triplets obtained with the same filter, separated by a temporal interval ranging from 0.5 to 8 days, were used for the tracking. Following the ring-plane crossing epoch in 1995, Saturn's orbital obliquity and ring projection limited our visibility of the northern hemisphere, so most features were observed from latitudes  $+30^\circ$  to  $-90^\circ$ . A total of 343 individual features (most with



**Figure 1** Images of different latitudes of Saturn, showing a representative variety of cloud features tracked to measure the winds. The HST WFPC2 images were obtained at different wavelengths, and in some cases their motions are indicated. The spatial resolution of the camera (PC mode) was  $0.0455 \text{ arcsec pixel}^{-1}$  ( $260 \text{ km pixel}^{-1}$  at Saturn). **a**, Polar projection. The pole is centred on the dark cap; the arrows mark the bright spots (at a wavelength of 890 nm) at latitudes ranging from  $250^\circ$  to  $290^\circ$  (each tick mark represents  $10^\circ$  in longitudinal extent). **b**, Temperate latitudes at a wavelength of 675 nm (the full latitude circles shown are  $235^\circ$  and  $250^\circ$ ). The globe cut shows regularly observed mid-latitude dark spots together with a bright spot (shown magnified in the inset to reveal its structure). **c**, Pair of images showing the zonal translation of two bright features at latitude  $229^\circ$  and at a wavelength of 439 nm. The full latitude circles shown are  $217^\circ$  and  $233^\circ$  (note the change in central meridian longitude between the

two dates). **d**, Cylindrical maps of the equator (from  $0^\circ$  to  $230^\circ$ ), showing a variety of features at a wavelength of 890 nm and their zonal translations (note again the changing longitude of the central meridian for each day). Separations between tick marks are  $10^\circ$  in longitude and  $5^\circ$  in latitude. The three white lines identify typical large-scale equatorial features in the three maps. In **b–d**, south is up and east is to the left. Longitudes in the central meridian are based on the System III radio rotation period, and latitudes are planetographic<sup>11</sup>. The longitudinal translation of each feature in **c** and **d** was converted to drift rate (degrees per day) and then to zonal velocity (see Fig. 2). If the features shown in **d** (first panel) had moved at the Voyager zonal velocities, they would be about  $40^\circ$  to the left of their marked positions in the second panel. This is substantially greater than the measurement uncertainty.



**Figure 2** Saturn's zonal (east-west) wind velocity profile at cloud level as a function of latitude. Data are shown for two different epochs (1980–81 and 1995–2002). The continuous line shows the averaged Voyager 1 and 2 profiles, as measured during 1980–81 (ref. 11). The large open circles represent individual measurements obtained from 1995 to 1997 by tracking large features using ground-based telescopes<sup>17</sup>. The small black dots are the individual velocity measurements obtained between 1996 and 2002 using HST images as reported in the text, with the error for each individual measurement added as a thin line. The wind speeds are determined relative to the radio rotation period of 10 h 39 min 24 s, assumed to be that of the interior. The main uncertainties in these data arise from image navigation (planetary limb fit), target misidentification, and cursor pointing on the feature. The errors in latitude positioning range from  $\pm 0.5^\circ$  in the equator to  $\pm 1.5^\circ$  at the poles. Wind speed precision is of the order of target size/tracking time; at our typical target size (500–2,000 km) and tracking times (minimum 0.5 d, maximum 60 d), this gives values ranging from  $\pm 1 \text{ m s}^{-1}$  to  $\pm 15 \text{ m s}^{-1}$  (see Supplementary Information for the full data for each point used in this figure).

sizes ranging from  $\sim 500$  to 2,000 km) were tracked. A sample of Saturn's cloud features observed at different latitudes and with different filters, and their tracked motions in the equator, are shown in Fig. 1.

In Fig. 2 we present our 1996–2002 measurements, and compare them to the Voyager wind profile<sup>11</sup>. We also include individual spot velocities obtained during 1994–97 from ground-based telescopes<sup>17</sup> (full wind speed data are available as Supplementary Information). First, the most evident and unexpected result is the truncation of the equatorial eastward jet to maximum velocities of  $\sim 275 \text{ m s}^{-1}$ , a drop of  $\sim 200 \text{ m s}^{-1}$  relative to the Voyager value. The deviation from the Voyager profile took place equatorward of latitudes  $\pm 17^\circ$ , although the jet itself is slightly broader, starting to change at latitudes  $\pm 25^\circ$ . Second, there are no apparent changes in the other southern eastward and westward jets, even in the 'ribbon' wave jet at latitude  $+47^\circ$  re-observed during 1994–96 (ref. 18). Last, we confirm the existence of a recently discovered south polar jet at  $-73^\circ$  latitude<sup>19</sup>, making Saturn's zonal jet system highly symmetric.

The HST profile is plotted using features measured with all filters and over the full time period indicated above. We do not find any dependence of wind velocities with wavelength, nor with time, during the observing period. The peak truncation has persisted since  $\sim 1994$ . The velocity dispersion

seen in the equatorial region from  $+5^\circ$  to  $-17^\circ$  (amounting in some places up to  $\sim 75 \text{ m s}^{-1}$ ) is probably real, and reflects intense local motions related to the disturbances in the equatorial area (also observed one month after the 1990 storm outbreak<sup>15</sup>). A detailed analysis of the equatorial cloud morphology showed that this period was characterized by the development of large-scale features ( $\sim 20,000 \text{ km}$  in zonal extent) with abundant internal structure (Fig. 1). This differs from the Voyager era, when the most representative cloud features were series of bright plume-like structures<sup>11</sup>. However, between both periods, 1980–81 and 1996–2002, a large storm erupted at  $+5^\circ$  in 1990 (refs 13–15), disrupting the equatorial region cloud morphology from latitudes  $+22^\circ$  to  $-5^\circ$ , and extending its activity during 1991 (ref. 20). It was followed by another intense storm centred at  $+10^\circ$  in 1994 (ref. 21), and by subsequent similar features during 1995–97 (ref. 17).

In order to determine the altitude of the features we see, we have carried out a radiative transfer analysis of the wavelength dependence of the reflectivity across selected latitudes from the equator to the south pole (from limb to limb), using the 'doublingadding technique'<sup>18,19,22</sup>. At  $-10^\circ$ , where the main jet speed velocity changes are seen, the model that best fits the reflectivity has a high stratospheric haze (altitude between 1 and 10 mbar), and below it, a thick layer of particles (haze or cloud) with optical depth  $\tau = 10$  located between 40 and 300 mbar. Deeper (1.8 bar), a putative ammonia cloud is placed. But the features that we see (that is, the cloud tops, where  $\tau \approx 1-2$ ) are located in the intermediate thick haze, nominally at pressures  $\sim 100$  mbar, close to the tropopause level<sup>23,24</sup>. According to cloud models of the equatorial region at the Voyager epoch<sup>25</sup> and before the development of the 1990 storm<sup>26</sup>, the equatorial haze layer reached  $\tau = 1$  in the level  $\sim 300$  mbar. Our analysis of the 1990 storm placed its cloud tops at 200 mbar (ref. 22). Thus, within the model uncertainties, the equatorial features we see in 1996–2002 are slightly higher than in 1980–81, probably by no more than a scale height ( $\sim 36 \text{ km}$ ).

The abrupt truncation of the eastward equatorial jet could be the result of a true temporal change in the general circulation due to unknown dynamical processes, or an indirect effect. One possibility is that the cloud systems in 1996–2002, placed at a higher altitude than in 1980–81, moved more slowly, according to the expected decrease in altitude of zonal winds measured in other latitudes<sup>23</sup>. Another possibility is that wave or disturbance propagation at cloud level in the equator, relative to the mean zonal flow, is affecting our velocity measurements. However, the historical large-scale equatorial storms (in 1876, 1933 and 1990) moved with speeds  $\sim 400 \text{ m s}^{-1}$  (refs 11, 20), close to the Voyager profile at the central latitude of the storms, indicating that such an effect was not present at least during the initial phase of the storm development.

The picture that emerges from our 1996–2002 measurements, when compared to the Voyager data for 1980–81, is that Saturn's equatorial dynamics and jet structure show high variability. It is the region where most of the large-scale storms form on the planet, and the place where the jet wind speed has changed by 42%, as reported here. Such a large wind speed variability has not been detected in Jupiter, where many more observations on jet

stability are available<sup>2,3</sup>. Outside the equator, our observations indicate that Saturn's jets appear to be stable in time. Compared to Jupiter, Saturn has fewer jets overall, but they show higher north-south symmetry in latitude and in speed intensity. Saturn receives less sunlight and releases less internal heat than Jupiter, but the sunlight source is more variable owing to the planet's obliquity. For example, the polar areas each alternately fall into darkness during the course of a half Saturn year, and the equator suffers the ring-shadowing insolation variability. All these differences between the planets need to be considered when developing future general circulation models for the jet origin in the giant planets.

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