

Depth of a strong jovian jet from a planetary-scale disturbance driven by storms

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The atmospheres of the gas giant planets (Jupiter and Saturn) contain jets that dominate the circulation at visible levels^{1,2}. The power source for these jets (solar radiation, internal heat, or both) and their vertical structure below the upper cloud are major open questions in the atmospheric circulation and meteorology of giant planets^{1–3}. Several observations¹ and *in situ* measurements⁴ found intense winds at a depth of 24 bar, and have been interpreted as supporting an internal heat source. This issue remains controversial⁵, in part because of effects from the local meteorology⁶. Here we report observations and modelling of two plumes in Jupiter's atmosphere that erupted at the same latitude as the strongest jet (23° N). The plumes reached a height of 30 km above the surrounding clouds, moved faster than any other feature (169 m s⁻¹), and left in their wake a turbulent planetary-scale disturbance containing red aerosols. On the basis of dynamical modelling, we conclude that the data are consistent only with a wind that extends well below the level where solar radiation is deposited.

Jupiter has been intensively surveyed since February 2007 using a battery of ground-based telescopes and the Hubble Space Telescope (HST) during the New Horizons spacecraft passage. Fortunately, HST images on 25 March 2007 captured the onset of an uncommon planetary-scale disturbance in the peak of the highest speed jovian jet at 23.5° N planetographic latitude, whose eastward velocity is typically between 140 and 180 m s⁻¹ relative to the System III radio rotation period^{7–11} (Fig. 1). In the peak of the jet, a small, round bright cloud with a size of 500 km (plume B) grew rapidly, implying from mass flux conservation an average vertical velocity of ~1 m s⁻¹ (ref. 12). The second plume, plume A, emerged less than 9.26 hours later at a distance of 63,000 km (55° longitude) to the east of plume B. If plume B had triggered plume A, the required propagation velocity of the triggering mechanism would have to be 1.9 km s⁻¹ or about 1.5 times the sound speed at 6 bar. Plumes A and B moved with speeds of 169 and 164 m s⁻¹, respectively. A pattern of slower moving dark patches and bright features with velocities in the range of 100 to 150 m s⁻¹ (Fig. 2) was shed sequentially in the wake westward of both plumes, forming the north temperate belt disturbance^{13–16}. The subsequent mixing of the clouds and aerosols formed a homogeneous and redder north temperate belt (Fig. 1).

The broad wavelength coverage (from the ultraviolet at 230 nm to the thermal infrared at 20.8 μm) allowed us to retrieve the physical properties of the plumes and surrounding clouds before, during and after the disturbance. Two radiative transfer codes were used to match the plumes' reflectivity and radiance—one for the visible and near-infrared (230 nm–3 μm) to retrieve cloud properties and top altitudes, and the other for the thermal infrared (8.7–20.8 μm) to retrieve temperatures, aerosol opacity and gaseous abundances (Fig. 1e). Particles at the top of the plume heads reached the 60 ± 20 mbar level—that is, about 15 km above the tropopause (which is located between 100–150 mbar) and 30 km above the 200–400 mbar layer (where a tropospheric haze containing the cloud features seen in the visible has its greatest altitude). Above the clouds, a thin stratospheric haze with a base at 40 ± 10 mbar extends upward, but apparently the plumes did not reach this haze. The plumes had high optical thickness (above 50), and best-fitting models give bright particles with a typical radius of 7 ± 1 μm (Supplementary Information). The 200–400 mbar tropospheric haze is formed by smaller particles (about 0.5 μm). During the disturbance, the tropospheric haze increased its optical thickness from 5 ± 1 to 10 ± 2, without changing its altitude significantly, but producing redder aerosols. We therefore conclude that the plumes' tops (Fig. 1d) are formed by fresh icy particles (probably a mix of Jupiter's condensable compounds: water, ammonia and NH₄SH) injected high by the virulent upwelling, and that the disturbance increased the aerosol density and formed a red chromophore—or mixed in a pre-existing chromophore.

The high temporal sampling of our observations allowed us to track (with unprecedented resolution) the changes in the jet velocity profile associated with the disturbance at cloud level: we did this for the day the disturbance erupted (25 March), during its development (March–May) and after its cessation (5 June). (The resolution ranged from 170 to 135 km per pixel on HST frames; Fig. 2.) Disturbance features from 22° to 26° N showed zonal velocities lower than the pre-disturbed jet (Fig. 2a), while the plumes moved faster than the jet peak. We interpret the pattern as the result of instability in the strongly meridionally sheared jet triggered by the rapidly moving bright plumes. The jet became more symmetric after disturbance cessation and the peak velocity decreased by only about 15 m s⁻¹

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(Fig. 2b, c), smaller than the change of $\sim 40 \text{ m s}^{-1}$ observed between 1979 and 2000^{7–11}. Our conclusion is that the jet remained robust against the turmoil generated by the disturbance evolution, suggesting that it extends deep below the upper clouds where motions are measured.

To test this hypothesis, we ran two different types of dynamical models. The first simulated plume formation using a three-dimensional moist convection code^{17,18} (Fig. 3a, b), exploring the atmospheric conditions that can lift the plumes to the high altitudes observed. Previous extensive simulations showed that solar water abundance and high humidities can drive storms to the tropopause but not higher¹⁷, and only if they develop in an environment that is not moist adiabatic¹⁹. To reach the 60-mbar level, we tested variations in the standard vertical temperature–pressure profile^{20,21}, and in ammonia and water abundances. A single updraft cell powered by moist water convection (cloud base level at 5–7 bar) requires 2–3 times solar water abundance with nearly 100% relative humidity and with a thermal profile 3–5 K colder than the reference temperature in the upper troposphere (at 200 mbar, Fig. 3b). The plumes might be formed by clusters of these cells²². Accordingly, the plumes are deeply rooted and extend vertically more than 120 km (from 60 mbar to 5–7 bar). Their fast zonal motion (169 and 165 m s^{-1}) reflects that of the wind at their base at 5–7 bar. Comparing the velocities at 0.3–0.4 and 5–7 bar indicates that the vertical wind shear below the upper cloud is low (increasing at about 4 m s^{-1} per scale

height of 20 km), consistent with the lifetime of the plumes. Under a strongly vertically sheared flow, our model shows that the upwelling is interrupted and the plumes do not develop. The results of the three-dimensional model were injected into a two-dimensional model reproducing the tail observed at the visible cloud level (Fig. 3c inset)²².

A second test of the vertical wind shear used the EPIC²³ general circulation model to simulate the structure and motions of the disturbance turbulent patterns (Fig. 3c). We used as an input the jet profile that was measured before the disturbance eruption (Fig. 2a). We tested the formation of the turbulent pattern by introducing a point heat source in the jet peak²⁴ on an atmospheric channel centred at the jet peak with two free parameters: the pressure level of the inflexion point where the vertical wind shear changes, and the value of this vertical wind shear. Above the clouds (from 0.6 to 0.01 bar), we assumed that the jet speed decreases as observed during the Cassini fly-by²¹. The formation of the turbulent pattern is very sensitive to the jet shape at cloud level. We tested this sensitivity by performing the numerical simulations with wind profiles measured at different epochs. Among them, the Cassini wind profile¹¹ and the 5 June HST profile were stable against the heat source perturbation. On the contrary, the jet profile we measured on the outbreak day (Fig. 2a) becomes rapidly unstable as we introduce the perturbation. Moreover, the disturbance pattern resembles the observed one when the inflexion point is at a pressure of 600 mbar (at the predicted

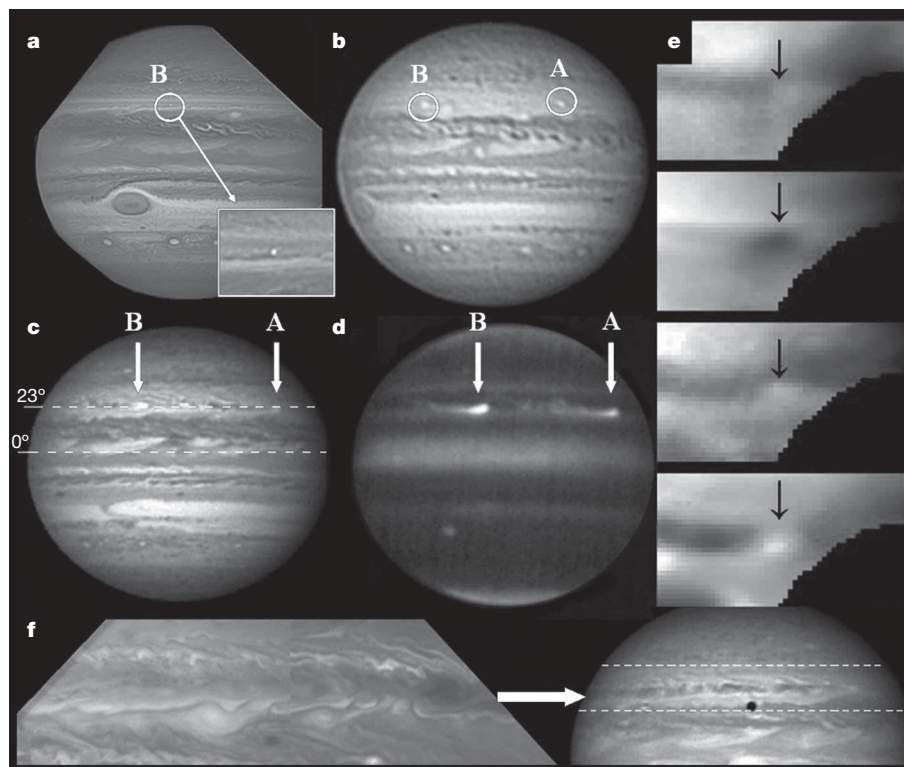


Figure 1 | Plume onset, growth and disturbance development (March–May 2007). **a**, Onset of plume B, 25 March (HST, 410 nm). **b**, Growth of plumes A and B, 27 March (IOPW, visible). Both plumes grew in ~ 1.3 days to a size of 2,000 km. Plume A was at $23.4^\circ \pm 0.5^\circ \text{ N}$ and moved with a speed of $169.2 \pm 0.5 \text{ m s}^{-1}$, and plume B was at $23.1^\circ \pm 0.5^\circ \text{ N}$ and moved with a speed of $164.3 \pm 1.7 \text{ m s}^{-1}$ (see Supplementary Information). **c**, Plumes and disturbances in their wake, 5 April (IOPW, visible). Both plumes were bright features in the visible (meridional extent of 2,500 km, 4,000 km zonal) and particularly prominent at wavelengths sensitive only to high-altitude levels. **d**, Plumes and their tails retrieved at high altitude (NASA-IRTF, $2.3 \mu\text{m}$ methane filter). **e**, Maps of plume A observed in the thermal infrared on 5 April (IRTF). These excerpts from cylindrical maps show the deviation from the zonal mean of the indicated parameters in the plume head region (top to bottom): temperature at 123.4 mbar, temperature at 393 mbar, aerosol

content above 600 mbar and ammonia abundance near 300 mbar. The plume produced lower temperatures near 392.9 mbar, but marginally higher temperatures at 123 mbar, as well as increased ammonia–cloud level aerosols and 300-mbar ammonia gas abundances. The arrows mark the plume head region. **f**, Turbulence and wavy patterns in the wake of plume A followed by the formation of a new north temperate belt as observed on 1 May by the Hubble Space Telescope (left, 410 nm, magnified view) and IOPW observers (right; the horizontal bars limit the area of the north temperate belt). The HST image shows the turbulent pattern formed at latitudes 20 – 28° N , with a predominant wavelength of 7,000–12,000 km. Plume B disappeared around the time the dark patches shed by plume A reached the location of plume B in about 14 days. The disturbance advanced to the west, encountering plume A on its eastern side on 11 May (its lifetime was 45 days), when it disappeared.

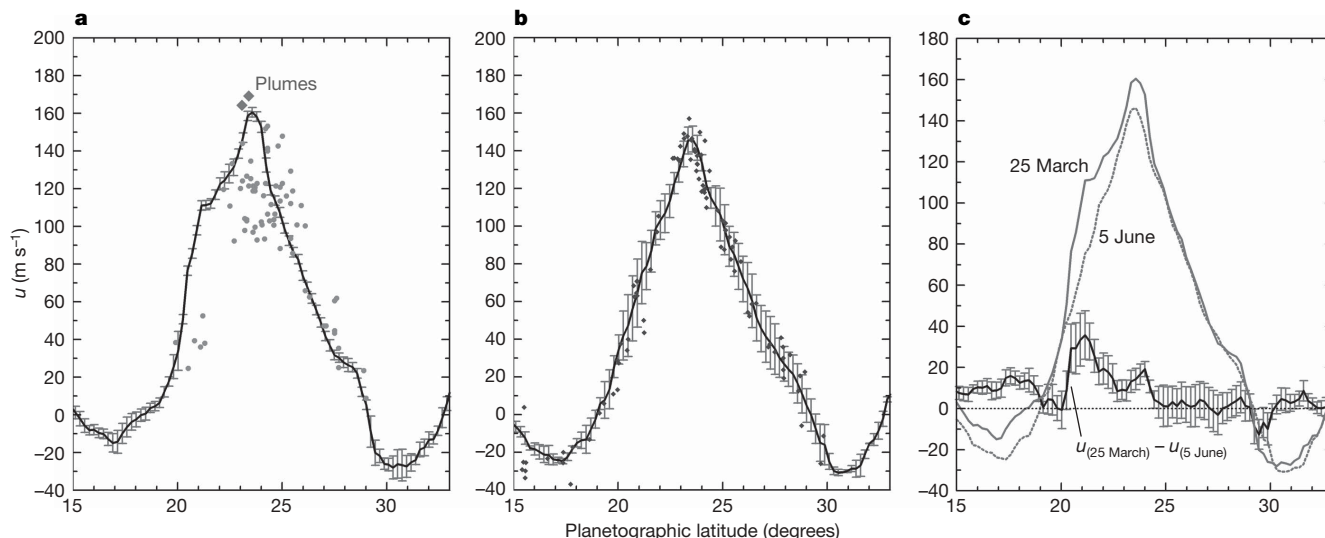


Figure 2 | Time dependence of the profile of the north temperate jet. **a**, Zonal velocity of the disturbance features (filled circles) and plumes A and B (filled diamonds) between 25 March and 31 May 2007 measured by cloud tracking, as compared to the profile the day of the eruption (continuous line, pre-disturbance stage on 25 March 2007) obtained by one-dimensional zonal brightness correlation on HST images (error bars represent the standard deviation of the measurements). **b**, Jet profile after the disturbance

ended, 5 June 2007. The continuous line represents the profile obtained by zonal correlation and the dots by cloud tracking, both on HST images (error bars represent the standard deviation of the measurements). **c**, Comparison of the jet profiles before the eruption (25 March 2007) and after the disturbance end (5 June 2007). The difference between both profiles as a function of latitude is shown as a darker line with associated error bars representing the standard deviation of the measurements.

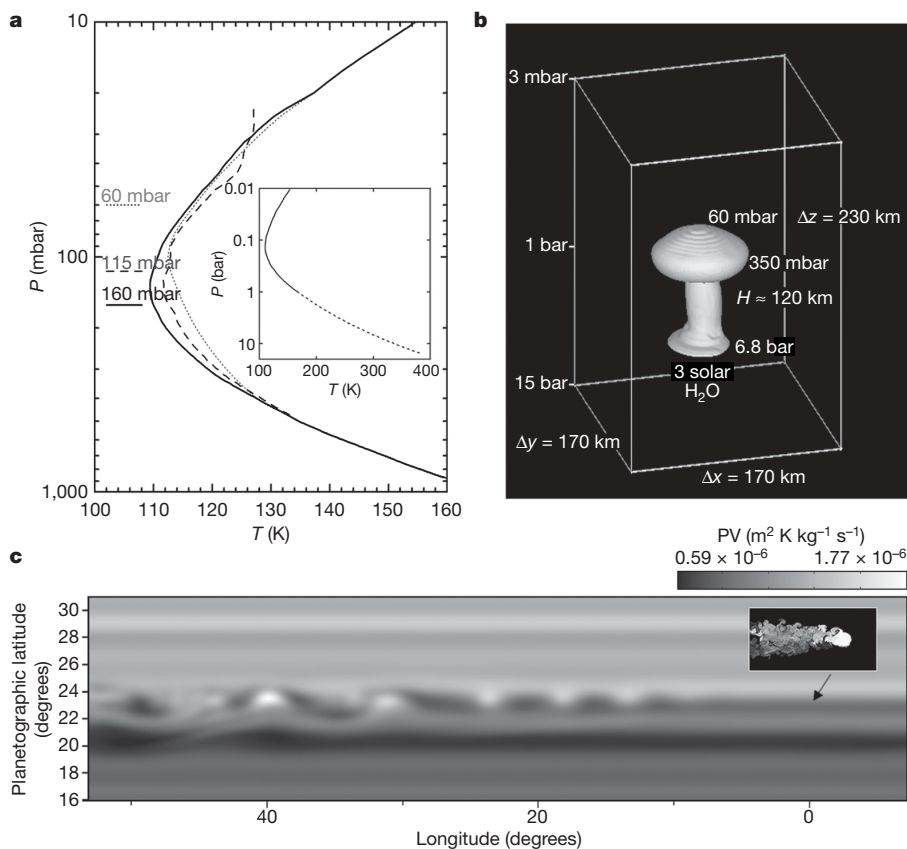


Figure 3 | Models of the plume onset and disturbance development. **a, b**, Wet convective three-dimensional model of the plumes. **a**, Thermal profiles used to run the simulations and the cloud top level reached by the convective cell assuming a deep water content of 3 times solar abundance and 95% of relative humidity above the condensation level. *P*, pressure; *T*, temperature. The continuous line corresponds to the Cassini CIRS thermal profile at the NTB location¹⁹, the dashed line to the Voyager IRIS thermal profile¹⁸ and the dotted line to a synthetic profile with less static stability from 500 to 200 mbar required for the storms to reach the 60 mbar level. The inset shows the wet adiabat extension deep in the atmosphere. **b**, Convective

cell resulting from the model able to fit the observed cloud tops of the plumes and the domain of simulation. **c**, The plume brightness distribution (inset) results from a two-dimensional model of a round cloud placed in the peak of the jet and evolving as it interacts with the meridional shear of the zonal wind¹⁷ with a spatial resolution of 5 km over a 10,000 × 5,000 km area. The map (main panel) shows the distribution of Ertel's potential vorticity (PV; greyscale) at 650 mbar after 30 days for a simulation where the jet extends vertically downwards with constant value from the upper cloud layer at altitude ~0.6 bar down to at least 5–7 bar (the location of the water clouds and the plume source). Inset and map are at the same scale.

ammonia cloud level) and the vertical wind shear down from this altitude to the water cloud base at 5–7 bar is zero or increases slightly with depth. This result reinforces the conclusion that the jet extends with low vertical wind shear down along the whole ‘weather layer’ to at least the 5–7 bar pressure level.

Our 5–7 bar zonal wind speed of 169–165 m s⁻¹ at 23° N is consistent with the 180 m s⁻¹ velocity determined for that depth by the Galileo probe⁴ at 7° N, as well as the 240 m s⁻¹ wind speed from previous EPIC simulations of the long-term behaviour of the 1990 disturbance²⁴. These studies agree that the winds do not decay below the upper ammonia cloud, and extend deeper than the solar radiation penetration level at 1–2 bar (see Supplementary Information), in agreement with previous ideas on the depth and stability of the jovian jet structure²⁵.

A comparison of this disturbance with two previous events in 1975 and 1990 suggests additional caveats and surprising similarities^{13,14}: first, the outburst occurred with an interval of ~15–17 years; second, the plumes always appear in the jet peak within ±0.5°; third, the disturbance erupted with two plumes (not one, three or more); fourth, the eastern plume, located in longitude east of the other (taking as a reference the shortest distance between both) is always the fastest; and last, the plumes moved with a speed in the range ~165–170 m s⁻¹ in all three events.

Received 30 July; accepted 29 November 2007.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank all the contributors to the International Outer Planet Watch (IOPW) observing programme for their efforts in the Jupiter imaging survey. This work was supported by the MEC PNAYA, Grupos UPV, CESCA (Barcelona) and Fondos FEDER. R.H. was supported by the ‘Ramón y Cajal’ programme. We acknowledge the HST director’s discretionary times. G.S.O. and P.Y.-F. were visiting astronomers at the IRTF, supported by the University of Hawaii and NASA.

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