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Renewed acceleration of the 24°N jet on Jupiter

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[Two tables, five figures]

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Running head: Jupiter's NTBs jet

Abstract

Jupiter's eastward jet at 24°N, which formerly had the fastest winds on the planet, has maintained a less extreme speed of ~135 m/s since 1991, carrying a series of long-lived vortices at 125 m/s. In 2002-2003, as the albedo of the adjacent North Temperate Belt increased, the tracks of the vortices accelerated slightly, and they had disappeared by 2005. In 2005, small tracers had a mean speed of 146.4 (+/- 0.9) m/s, significantly faster than the previous mean speed of the jet, suggesting that the jet peak itself has accelerated at cloud-top level, and that the jet is beginning to return to the super-fast state. These changes may resemble the even greater transformations occurring in the equatorial jet of Saturn.

Key words: Jupiter, atmosphere; Saturn, atmosphere; Atmospheres, dynamics.

1. Introduction

The eastward jet at 24°N on Jupiter, named the NTBs jet as it delimits and defines the North Temperate Belt south edge, is remarkable for two reasons. First, it has had the fastest cloud-top wind speeds of any jet on the planet, measured at ~182 m/s by the Voyagers (Maxworthy, 1984). Second, it can exist in an alternative, less extreme state: when the profile was remeasured in 1995-2000 by the Hubble Space Telescope [HST] and Cassini, the peak speed had been reduced to ~135 m/s (Simon, 1999; Garcia-Melendo et al., 2000; Porco et al., 2003).

Moreover, while the spacecraft showed that these were the true peak speeds of the jet at cloud-top level, ground-based observations indicate that these speeds represent two different states which have alternated during history (Rogers, 1995). The 'super-fast' speed range (North Temperate Current D), seen by the Voyagers in 1979, was repeatedly observed from 1970 to 1990. It was characterised by intermittent vigorous outbreaks lasting only a few months, which included very bright spots travelling close to the peak speed of the jet (~162-177 m/s), as well as slower dark spots, and episodes of yellow or orange coloration of these latitudes. A similar outbreak reaching at least 148 m/s, with orange coloration, had been observed a century earlier, in 1880, implying that ground-based observers could have recorded the super-fast state during the early twentieth century if it had prevailed then. In contrast, the observations from this interval showed only the slower North Temperate Current C, in 1891-92 and intermittently from 1926-43, as well as from 1991 onwards. These intervals were characterised by outbreaks of small dark spots only, sometimes lasting more than a year, without vivid colour. Their speeds were fairly constant at 122-129 m/s, again just less than the peak jet speed of ~135 m/s as observed by HST and Cassini.

The most recent transition between current D and current C states occurred in 1990-91. The last and best observed of the current D outbreaks was in early 1990 (Sanchez-Lavega et al., 1991; Rogers 1992a, 1995). Less than 2 years later, a series of small dark spots appeared in autumn 1991, whose morphology and motion were typical of current C activity (Rogers & Foulkes, 1994; Garcia-Melendo et al., 2000). This activity persisted until at least 2002. Although it was not possible to track all the spots continuously in the early 1990s (partly due to limited resolution, and partly due to diversity in their motions), from 1996 onwards there were just 7 long-lived spots with steady motion at 124-126 m/s (Garcia-Melendo et al., 2000; & our reports in the *Journal of the British Astronomical Association*, most recently: Rogers et al., 2003, 2004). Imaging by HST (Simon, 1999; Garcia-Melendo et al., 2000) showed that the seven spots represented anticyclonic vortices at 23.2°N, 2.6° wide in latitude, with tangential velocity of ~18 m/s, 'rolling' along the south side of the jet. The peak speed of the jet was ~135 m/s, at 23.7°N throughout this time. This pattern persisted at least up till 2000 (Garcia-Melendo & Sanchez-Lavega, 2001; Porco et al., 2003). It was clear that 135 m/s was the physical speed of the jet at the level of the visible clouds, in view of (i) the smooth jet profile revealed by the HST and Cassini observations, (ii) the low albedo of the adjacent NTB during these years (which implied that the super-fast jet was not simply obscured by overlying cloud), (iii) the relationship of the jet to the vortices as summarised above, and (iv) the resemblance to jets in other latitudes which display anticyclonic vortices running close to the peak jet speed.

At least three other major jets intermittently carry such anticyclonic vortices. The rapid speeds of these 'jet-stream spots', close to the peak velocity of each jet, are entirely distinct from the much slower speeds of the majority of vortices on the planet relative to System III (Rogers, 1995; MacLow and Ingersoll, 1986; Morales-Juberias et al., 2002; Li et al., 2004). In fact, on the well-observed prograding jet at 35°N, the speed of these spots has varied very little during recorded history and is consistently 7-11 m/s slower than the peak of the jet itself as observed by Voyager or HST (Rogers 1995; Rogers et al., 2004), just as with the NTBs jet.

We now report high-resolution ground-based observations which show the disappearance of the long-lived vortices and renewed acceleration of the jet itself at cloud-top level.

2. Observations and analysis

Observations were made by amateur observers imaging at visible wavelengths with telescopes of apertures 200-410 mm, using CCD cameras or webcams (Grafton, 2003; David and Stamp, 2003). Details of the observers and their equipment will be given in our regular reports on each apparition in the *Journal of the British Astronomical Association*.

Longitudes and latitudes of spots were measured using the PC-/WinJUPOS program, <http://jupos.org> (Rogers and Mettig, 2001). Longitudes were measured in System I, as this is the standard system with the rotation speed closest to the features of interest. Latitudes were zenographic. Drift rates were converted to u (m/s) in System III, assuming a latitude of 23.5°N which is our average for the features of interest, according to the formula:

$$u = (221 - DL1) / 2.245$$

If the conversion were performed for a latitude of 23.7°N, i.e. the jet peak reported by previous authors, the effect would be to subtract 0.2 m/s from our wind speeds.

In all images, south is up and longitude increases to the right.

3. Results

3.1. Disappearance of the 7 long-lived spots

The continuous tracking of the 7 long-lived spots has been reported from the mid-1990s up to 2001 (Garcia-Melendo et al., 2000; Rogers et al., 2003, 2004 & references therein). In ground-based images the vortices themselves were usually not resolved, because of their low contrast. Instead, the vortices were tracked by identifying a 'projection' from the low-albedo NTB which was drawn southward at the east (preceding) end of each vortex. Sometimes this was a distinct projection but sometimes it was a diffuse fringe or merely a discontinuity in the belt edge. Nevertheless, systematic measurements of all such features clearly demonstrated that there were 7 long-lived loci (Fig.1) and that they corresponded to the 7 vortices resolved by spacecraft (Fig.2). In 2001/02 the NTBs belt edge was at 25.8°N (± 0.2°) and the dark projections or spots were recorded at 23-26°N, consistent with them being on the north-east sides of the vortices, which were known to be centred at 23.2°N.

The first sign of change came in 2002 December as the low-albedo NTB disappeared, being replaced by white cloud, and the 7 dark projections also ceased to be visible. From 2003 January onwards, only small inconspicuous dark spots and streaks could be tracked in this latitude range, without visible organisation. However when their longitudes were plotted, they were found to be concentrated in at least 3 loci travelling at 130 m/s (Fig.1; Table 1), indicating persistent disturbances which were consistent with the extrapolated tracks of long-lived vortices, which had accelerated slightly as the NTB whitened. The mean latitude of these faint features was 23.5°N (± 0.1°).

In early 2004 the pattern was very similar, with faint transient streaks clustered in several loci of which at least three were still consistent with disturbances on the extrapolated tracks of 3 long-lived vortices. The mean latitude was 23.2°N (± 0.2°), identical to the previous latitude of the vortices themselves.

In 2005, these faint little streaks no longer clustered on persistent tracks. Given that many such streaks were again recorded in high-resolution images, but scattered in longitude it is reasonable to conclude that the long-lived vortices had ceased to exist.

3.2. More rapid features

While the long-lived loci accelerated only modestly, individual small spots or streaks at ~23.5°N were observed to drift significantly faster, as observed in early 2003 and again in early 2004. They had speeds of ~141 m/s (Table 1, lower panel; Fig.3). They were arising in the long-lived loci and running ahead of them. An example is shown in Fig.4a, where the long-lived locus is temporarily marked by a grey streak and then by a tiny white spot, while a tiny grey spot progrades from it.

These speeds are likely to represent the peak speed of the jet, determined to be ~135 m/s at 23.7°N by HST observations in earlier years (see Introduction). If so, the jet was still ~10 m/s faster than the vortices carried along with it (Fig.5).

In spring 2005, there was no evidence of the long-lived vortices, but at least 5 small spots at ~23.5°N showed speeds of ~146 m/s (e.g. Fig.4b; details in Table 2). This mean speed is significantly faster than at any time since 1995, and possibly faster than at any time since 1990 (Fig.5).

4. Discussion

The present observations demonstrate that the NTBs jet, as observed at cloud-top level, has accelerated (Fig.5). Our mean speed of 146.4 (±0.9) m/s, in 2005, is significantly faster than the mean peak speed of 135 (±5) m/s observed by HST in 1998 (Garcia-Melendo et al., 2000). Although earlier HST values were less precise due to short observing spans, there are two reasons for believing that the value of 135 (±5) m/s applied throughout the mid-1990s. First, it represents the consensus of the reports (Simon, 1999; Garcia-Melendo et al., 2000; Garcia-Melendo & Sanchez-Lavega, 2001). Second, it accords with the close relationship of the jet to the adjacent long-lived vortices, which maintained a near-constant speed of 125 (±2) m/s throughout those years (Fig.5).

Our observations do not determine the latitudinal profile of the jet, and indeed it is possible that the peak in 2005 was even faster than we have measured, at a latitude that lacks visible tracers. We think this is unlikely for two reasons. First, Fig.5 suggests a smooth acceleration from the mean peak value observed by HST, always being 10 m/s faster than the long-lived vortices. Second, our observed latitude of 23.5°N is very close to the latitude of the peak observed by HST (nominally 23.7°N, but in fact showing a broad peak from 23.2 to 23.8°N) (Garcia-Melendo et al., 2000; Garcia-Melendo & Sanchez-Lavega, 2001).

Is it possible that the acceleration could be an illusion, due to a change in the nature or depth of the cloud tracers? If HST detected a real range of speeds of features within the jet, perhaps only the very fastest are now detectable from Earth. This seems implausible, as the typical scatter of ±~10 m/s in HST data (e.g. Fig.5 of Garcia-Melendo et al., 2000) is largely attributable to the short observing spans and, perhaps, to local motions within the jet peak; there is no evidence that populations of tracers with different speeds were confused. Alternatively, perhaps we are now detecting features at a deeper level where the winds are permanently faster. The jet may be faster below cloud-top level, by analogy with the jet at 7°N into which the Galileo Probe entered, and according to the modelling of Garcia-Melendo et al. (2005). But if there had been an attenuation of cloud cover allowing us to view deeper levels, one might expect a decrease in albedo. Instead, the albedo on the north side of the jet increased in 2002-03, and has not undergone obvious change since. So the most straightforward conclusion is that the jet itsself has accelerated at the visible level.

These remarkable changes in the NTBs jet may shed light on the wider problem of the dynamics of jets on giant planets. Although there are now theoretical frameworks for understanding the approximate dimensions of the jets, and the maximum speeds of the retrograde jets, it is still unclear how the latitudes and speeds of the prograde jets are maintained as precisely as they are (Vasavada & Showman 2005). The anticyclonic vortices which commonly appear on these jets may represent a mechanism by which the speeds are limited.

The dual-speed behaviour of the NTBs jet has instigated several theoretical models, particularly to explain how dark spots with 'current C' speeds appeared during the 'current D' outbreak in early 1990. Asada et al. (1993) interpreted these spots as gravity waves, so their phase speed would not represent any change in the jet speed. Garcia-Melendo et al. (2005) modelled them as vortices, appearing within the super-fast jet when it was destabilised by a heat impulse from below. This model gave a more realistic appearance, and produced vortices drifting with correct speed (their Fig.7). However, to maintain the vortices they still had to maintain the current D jet speed (and indeed, an even faster speed below the cloud-tops), so the massive reduction in observable wind speed still requires further theoretical elucidation. Observationally it is not clear whether the dark spots that appeared in early 1990 were the same vortices observed from late 1991 onwards: no such spots were detected in the 1990/91 apparition (Rogers 1992b).

To indicate promising directions for further modelling, we discuss from an observational perspective why the renewed acceleration has coincided with the change in albedo and the disappearance of the long-lived vortices.

The albedo change (whitening of the NTB) has occurred at intervals of ~10 years throughout history (Rogers, 1995), and has not shown any general relationship to outbreaks of spots in either current C or D. The 1990 current D outbreak is the only one which definitively terminated a high-albedo episode. Therefore, the meteorological change to higher albedo is probably not generally associated with faster wind speed. However, it may have provided permissive conditions that facilitated a transition in 2002-03.

We conjecture that currents C and D do indeed represent alternative quasi-stable states of the jet. Current D is the fastest possible, and is subject to repeated energetic outbreaks, which eventually (as in 1990) lead to the breakdown of the super-fast jet, possibly via turbulent mixing and generation of vortices. This is in line with the modelling of Garcia-Melendo et al. (2005), who found that the Voyager (current D) profile was unstable to heat impulses and liable to generate vortices, whereas the HST (current C) profile was not. Current C is more similar to other prograde jets, in terms of latitudinal gradients of speed and ambient vorticity, and like them it can carry anticyclonic vortices at almost the peak speed of the jet; in this state it was extremely stable from 1991 to 2002. Its speed may be the maximum that can sustain these stable vortices, although there is still not a complete physical model of this situation. However a gradual input of energy tends to 'pump up' the jet. With the breakup of the long-lived vortices (perhaps triggered by the meteorological change in the NTB), our conjecture is that the jet is now free to resume acceleration back towards the current D speed.

This scenario resembles the even greater change that seems to have occurred in the even larger equatorial jet of Saturn. The apparent peak speed of Saturn's equatorial jet was reduced from 470 m/s (1980-81, Voyager) to 280 m/s (1996-2002, HST) (Sanchez-Lavega et al., 2003), following the Great White Spot outbreak that transformed the equatorial region in 1990. Interpretation of this change has been complicated by concurrent changes in the levels of the observed clouds: Cassini measurements span this full range of speeds with instruments sensing different atmospheric depths, and the apparent change in cloud-top speeds is partly attributable to the appearance of high-altitude clouds since 1990, at a level where speeds are always slower due to vertical wind shear (Porco et al., 1995; Baines et al., 2005). However, it appears that vertical wind shear cannot explain the full magnitude of the change (Flasar et al, 2005; Perez-Hoyos & Sanchez-Lavega, 2006). As Great White Spots have erupted in Saturn's equatorial zone at intervals of 57 years (2 saturnian years), it would not be surprising if a gradual return to the pre-1990 state were to be observed. Thus there are parallels between the saturnian and jovian jets in the super-fast state terminated by an energetic convective outburst, and the less rapid stable state thereafter, and the historical cyclicity to these events. Observations of both of these jets over the coming years may facilitate a common understanding of the dynamics on both planets.

5. Acknowledgements

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Table 1. Measured speeds in NTBs jet, 2003-2005

	N	*DL1*(deg/mth)			*u* (m/s)			*Lat.*	
		mean	min	max	mean	min	max	(mean)	(± s.e.m.)
Vortex loci:									
2002/03	3	-70	-68	-73	129.6	128.7	130.9	23.5	0.1
2003/04	6	-75	-74	-76	131.8	131.4	132.2	23.2	0.1
Single spots:									
2002/03	7	-96	-93	-101	141.2	139.8	143.4	23.6	0.13
2003/04	8	-98	-96	-103	142.0	141.2	144.3	23.3	0.18
2004/05	5	-108	-106	-111	146.4	145.6	147.8	23.5	0.32

Speeds are expressed in System I (*DL1*; degrees per 30 days), and in System III (*u*; m/s).
Conversion is done assuming zenographic latitude 23.5°N.
The uncertainty in speed is typically ± 2°/month in *DL1*, or ± ~1 m/s in *u*.
The uncertainty quoted for the latitudes of vortex loci is the standard error of the mean for all measurements of spots in the loci. The uncertainty quoted for the latitudes of single spots is the standard deviation of the means for individual spots.

Table 2. Individual rapid spots measured in 2005

No.	*DL1* (deg/mth)	*u* (m/s)	*Lat.* (deg.N)	*s.d.* (deg.)	*n*	Dates 2005
1	-106	145.6	23.4	0.3	9	Apr 20–May 20
2	-111	147.8	23.0	0.4	6	Apr 23–May 4
3	-109	146.9	23.5	0.6	7	Apr 21–30
4	-107	146.1	23.8	0.4	6	Apr 16–May 2
5	-106	145.6	23.7	0.5	9	May 17–31
Mean	-107.8	146.4	23.5	0.3		

Uncertainty in drift values is typically ± 2°/month, i.e. ± ~1 m/s.
n, number of observations.

Figure 1

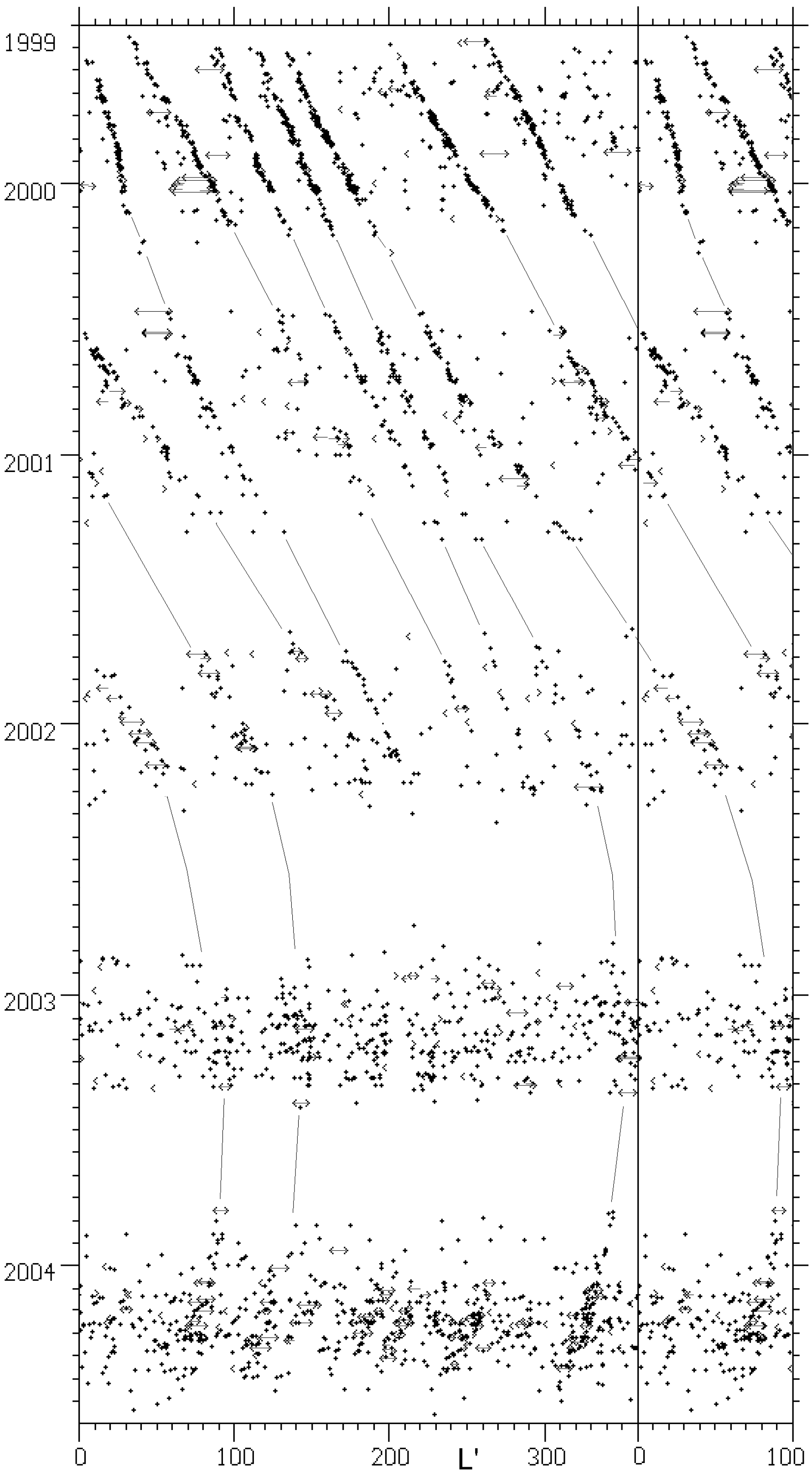

Fig.1. Feature tracking in the latitude range 22-26°N, from 1999 to 2004. Longitude scale is System III minus 9.67°/day. Time scale is marked at the start of each month. Dots are small dark projections or spots or streaks; <-->, E and W ends of faint dark streaks (with lines to show the extent of the streak). The well-defined tracks up to 2001 are the loci of the 7 long-lived vortices, each represented by a dark projection from the NTB on the north-east side. From 2003 onwards, after the NTB disappeared, the features are small faint spots or streaks (measured in large numbers due to the improved quality of the images). Their clustering suggests that several of the vortices persisted until 2004. The 2005 data are not shown as there was no clustering; see Fig.3.

Figure 2

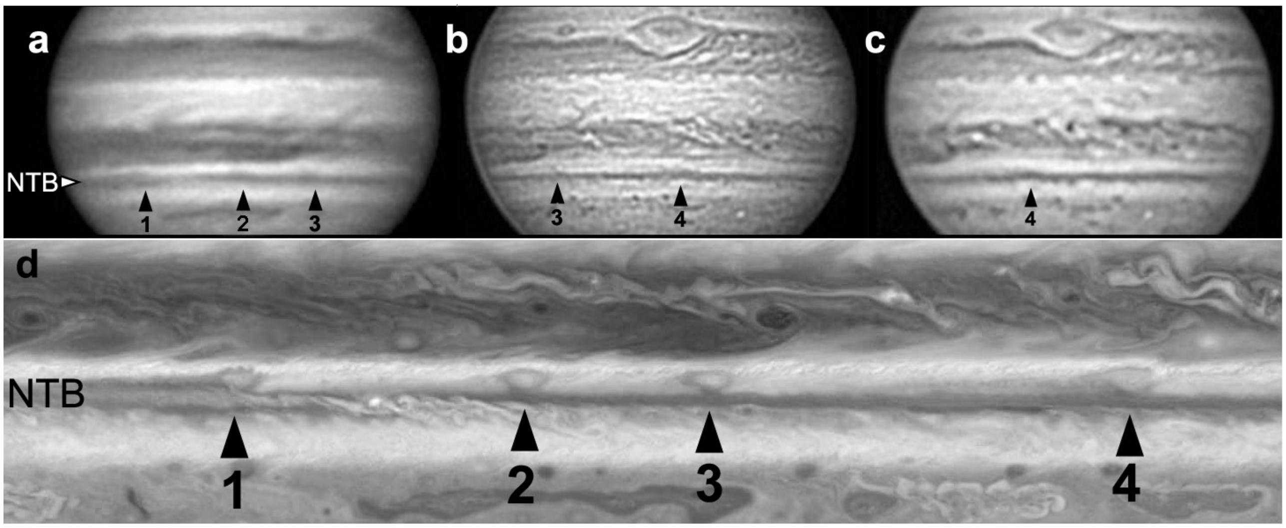

Fig.2. Images showing the vortices on NTBs in 2000 December. (a-c) Ground-based images in white light. Features tracked on the NTBs edge are marked by arrowheads 1 to 4. South is up in all images. (a) Dec.10, 22:42 UT; J.R. Sanchez (Spain). (b) Dec.11, 00:14 UT; A. Cidadão (Portugal). (c) Dec.13, 01:59 UT; D.C. Parker (Florida).

(d) Cassini map, 2000 Dec.11-12. This is a section from a blue-light map (Cassini public release PIA07782). Arrowheads indicate the vortices. Note the dark material preceding (left of) vortices, especially numbers 1 and 4, which correspond to the dark 'projections' seen in ground-based images. (Their positions relative to features in adjacent belts may differ from those in (a-c) because of the relative motion of ~10°/day.) Latitude range is ~5-40°N. Longitude marks are at 30° intervals. The map is from NASA, JPL, and the Space Science Institute, Boulder (Cassini imaging team, leader C. Porco).

Figure 3

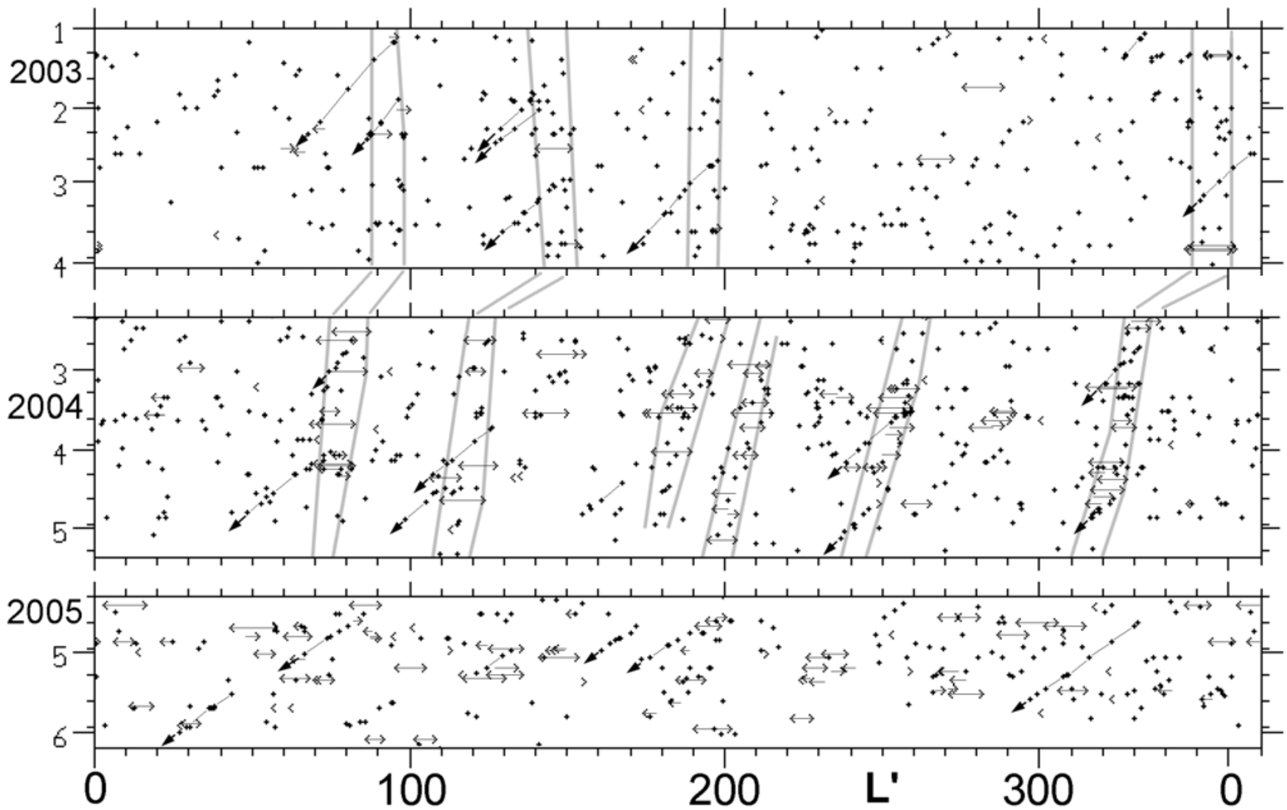

Fig.3. Feature tracking in the latitude range 22-26°N, from 2003 to 2005. Longitude scale is System III minus 9.67°/day. Time scale is marked at the start of each month. Symbols: +, small dark spots or streaks; < >, E and W ends of faint dark streaks (with lines where useful to show the extent of the streak). Pairs of near-vertical grey lines outline the long-lived loci (see Fig.1). Diagonal arrows indicate the ends of faster tracks for individual spots. Other such features probably had similar speeds, some being indicated by lines connecting points.

Figure 4

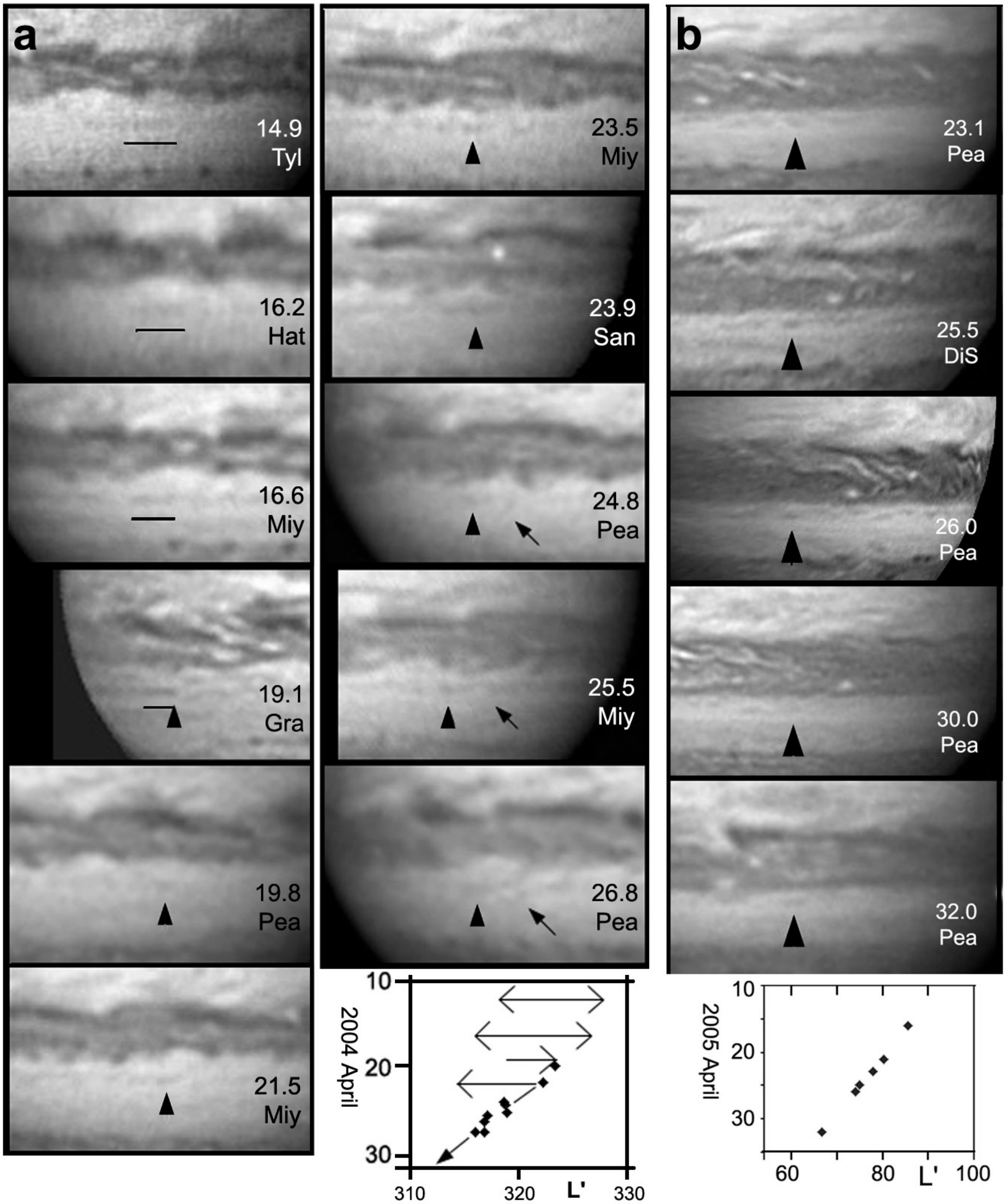
a
14.9
Tyl
16.2
Hat
16.6
Miy
19.1
Gra
19.8
Pea
21.5
Miy
23.5
Miy
23.9
San
24.8
Pea
25.5
Miy
26.8
Pea
b
23.1
Pea
25.5
DiS
26.0
Pea
30.0
Pea
32.0
Pea
2004 April
10
20
30
310
320
330
L'
2005 April
10
20
30
60
80
100
L'

Fig.4. Examples of the small features tracked in the NTBs jet, all at ~23.5°N.

(a) 2004 April (white light); (b) 2005 April (red plus green light). Each panel is an excerpt from an image, with no reprojection, except for 2005 April 26.0 which has been rotated to put the feature near the central meridian. Each panel is labelled with the decimal UT date (in April), and an abbreviation of the observer's name: G. Di Scala, J. Hatton, I. Miyazaki, D. Peach, J.R. Sanchez, D. Tyler. Each panel spans latitudes ~0-40°N, so as to show the motions of the indicated features relative to the large dark projections near the equator (at top). The rightward drift of the latter projections between panels indicates that the well-known north equatorial current, defined by their motion, is less rapid than the NTBs jet, visualised by the indicated features. At the bottom of each set is a chart of longitude versus time for that spot, enlarged from Fig.3.

(a) 2004 April: Initially there is a long dark streak which lies at the long-lived locus (underlined). The new spot (arrowhead) arises within it on April 19 and drifts faster. Although it is not possible to visualise any long-lived structure at the long-lived locus, a tiny white spot remains there for some days (oblique arrow).

(b) 2005 April: A small dark streak (arrowhead) is tracked; another less regular streak precedes it (to the left).

Figure 5

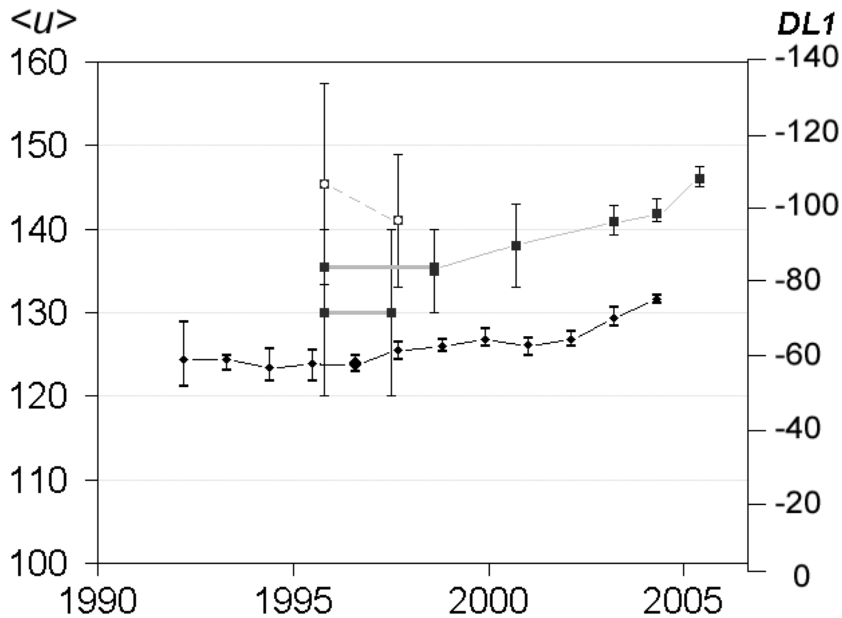

Fig.5. Speeds measured for the NTBs jet and associated vortices, from all sources, 1991-2005. *Diamonds (lower points)*: long-lived features, i.e. the 7 vortices and the persistent loci which probably represented their final stages. These are our data, with mean and actual range, from reports published in the *Journal of the British Astronomical Association*, and unpublished data for 1993, 1994, and 2001 onwards; except for 1996 where the value plotted is the mean for 1995-1998 from Garcia-Melendo et al.(2000).

Squares (upper points): small tracers which appear to represent the peak wind speed. The data from 1995 to 2000 are from HST, with error bars, as given by Simon (1999) (open squares), and Garcia-Melendo et al.(2000) and Garcia-Melendo and Sanchez-Lavega (2001) (filled squares; they quoted means for 1995-97 and 1995-98, indicated by thick grey lines, and individual values for 1998 and 2000). The data from 2003 to 2005 are ours, with the actual range of measured speeds.