Influence of Jupiter's South Equatorial Disturbance on jetstream speed

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A report of the Jupiter Section (Director: John H. Rogers)

The eastward jets on Jupiter are, with few exceptions, remarkably invariant. However, we now report considerable diversity of speeds in one of the fastest jets, at 7°S. We present ground-based observations from 1999 to 2006, which are shown to agree with measurements of the same region from *Cassini* spacecraft images. All the measurements refer to small cloud features seen as 'chevrons' in spacecraft images, which appear to represent the peak speed of the jet at or near cloud-top level. Previous discrepancies in measurements for this jet are resolved by showing that the speeds vary with longitude relative to a large wave-like feature, the South Equatorial Disturbance (SED). The SED has persisted from 1999 to 2006, and a similar feature was present during the *Voyager* flybys. When the SED is present and active, as it was during the *Voyager* and *Cassini* flybys, the observed jet speed is slow to the east of it (~116–128 m/s) but rapid to the west of it (~142–162 m/s). When the SED is absent (as in the mid-1990s) or weak (as in 2002–2005), it no longer modulates the observed speeds in the jet: a rapid jet speed of ~155 m/s is observed at all longitudes, but some individual features move more slowly over shorter intervals. These velocity patterns have implications for the physical nature of the SED and for the vertical structure of the jet at 7°S.

Introduction

The most well-defined and constant features in Jupiter's atmosphere are the eastward jetstreams (jets). They are generally assumed to have the same speed at all longitudes, and so far there has been no clear evidence to the contrary from spacecraft velocity measurements. However, the rapid jet at 7ºS that delimits the South Equatorial Belt north edge (SEBn) sometimes carries a unique, slower-moving feature, the South Equatorial Disturbance (SED), and we have reported a range of velocities for features in this jet.[1,2] This paper constitutes our third report on the SED.

The SEBn jet normally carries a series of tiny dark projections or chevrons with a spacing of ~4–8º longitude (5000–10,000km), and these are the principal features which reveal its motion.[3–12] They are visible in most images from the *Voyager* spacecraft, Hubble Space Telescope (HST), and *Cassini*, and were viewed in detail by the *Galileo* orbiter on 1996 Nov 5.[8] The chevrons are V-shaped dark markings with the apex of the V pointing east at the peak of the jet, tracing out the velocity profile of the jet as plotted from these spacecraft images. In the *Galileo* images, the north arm of the V was faint, whereas in the *Cassini* images, the north arm was darker and appeared as a dark projection curving north-west from the SEBn edge. The chevrons were the features tracked to deduce the zonal speed in *Voyager* images[3] and they will also have dominated other spacecraft measurements of the speed at this latitude. As these spacecraft-derived speeds were consistent down to the smallest scales, and had smooth profiles with respect to latitude, they are generally taken to represent the physical speed of the jet at cloud-top level.

In spite of these clearly visible features, there has been some debate about the exact speed of the jet (see Table 1 and ref.10). Measurements from HST in 1994–1998 consistently averaged 150–155 m/s.[7,9,10] Measurements from *Voyager* in 1979 were much more diverse, ranging from 128 m/s to 160 m/s.[3–8] The *Galileo Orbiter* in 1996, although it could not establish the absolute speed because of its restricted capability for returning images, showed a definite change in the profile of the jet since the *Voyager* observations.[8,10]

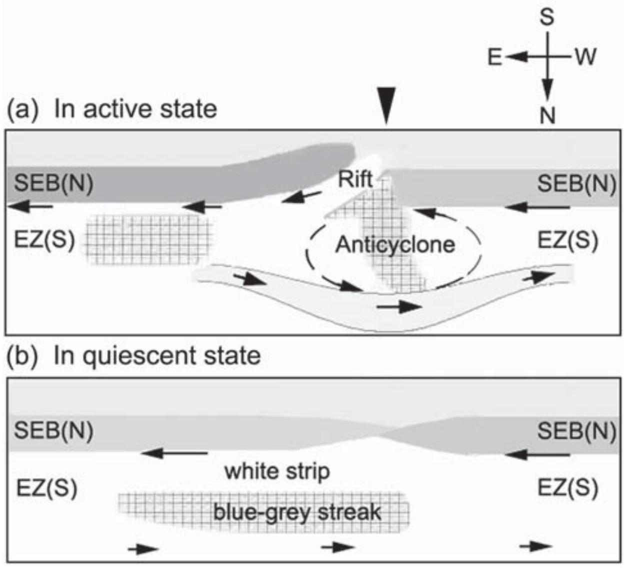

Figure 1. Diagrams of the typical visual appearance of the SED. **(a)** At times when it is highly active (adapted from ref.2). **(b)** At times when it is quiescent.
The large arrowhead at top indicates the adopted longitude of the SED (main complex). Arrows indicate directions of flow relative to the SED. Cross-hatching indicates variable blue-grey patches or streaks.

The possibility that these speeds may vary with time and longitude has arisen from observations of the South Equatorial Disturbance (SED). This is a large coherent long-lived wave with a drift rate much slower than the speed of the jet in which it is embedded. It appeared in 1999 and has persisted up to 2006. We have described it in detail in reports for the 1999/2000 and 2000/2001 apparitions.[1,2] It moved at +37 to +25°/month relative to System I, or 88–94 m/s relative to System III, much slower than the jet itself. When most conspicuous in 1999/2000, it produced a 'stormy sector' preceding it, which was strikingly disturbed in visible light around a large part of the circumference of the southern equatorial zone [EZ(S)]. The stormy sector was also diffusely dark in methane bands, indicating disruption of the high-altitude haze layer. However these effects were transient, and apparently all emanated from a 'main complex' which was marked frequently by a bright 'rift' in the SEBn edge, and most consistently by some kind of discontinuity in the SEBn edge and a bluish patch and/or streak in the EZ(S) (Figure 1). *Cassini* images showed that the main complex included an anticlockwise (anticyclonic) circulation in the EZ(S) (A. Vasavada, *pers. com*.),[2] the bluish patch or streak being associated with this.

A feature with an identical circulation pattern was observed by *Voyager* in 1979,[4,13] and we therefore believe it was a similar SED, even though it had a different albedo pattern, being dominated by a 'great white spot'. It persisted from 1976 to 1989.[14,15] Previous papers have discussed the similarity of this disturbance to the present SED, and to the periodically spaced dark patches (hot spots) on the approximately symmetrical jet at 7ºN.[2,6,16] It seems that the essential feature of the SED is the discontinuity in the SEBn edge (which we take to define the longitude of the SED) and, quite possibly, the associated anticyclonic circulation in the EZ(S), although this is not observable except by spacecraft.

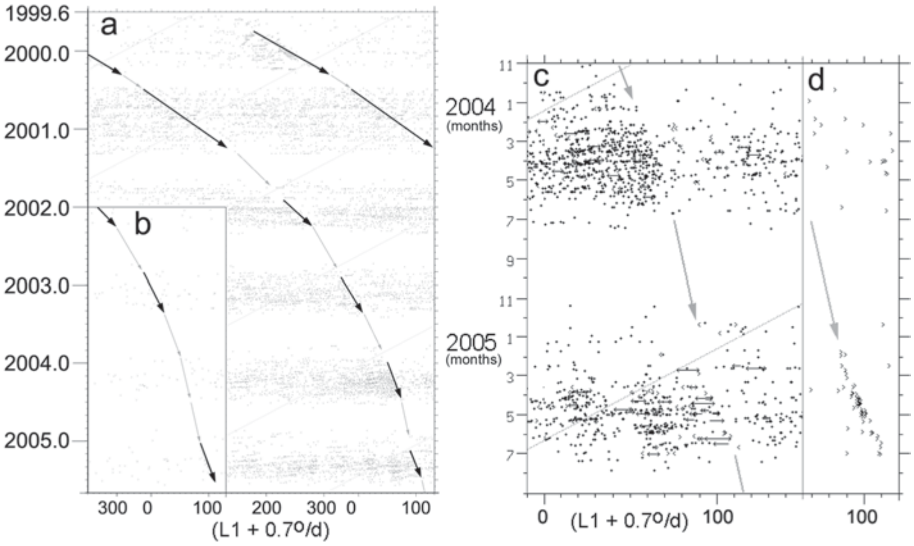

Figure 2. Longitude charts showing the persistence of the SED, 2000–2006.
(a) The track of the SED (main complex) is marked by arrows: black where distinct, grey where indistinct or interpolated. The grey background is a reduced-scale longitude chart of all dark spots at latitudes 5.0 to 8.0ºS. The SED (main complex) marks the interface between a dense area of points to the left (east) and a sparse area to the right (west).
(b) Longitude chart of the west ends of dark streaks in EZ(S), latitudes 3.0 to 6.0 ºS, with same scales. When the SED is indistinct in (a), it is marked by a distinct track in (b).
(c,d) Full-resolution portions of charts (a) and (b) respectively. In 2004 the SED was distinct as an interface on the chart of SEBn dark spots (a,c); in 2005, instead, it was represented by a streak in EZ(S) (b,d).
In all panels, longitude scale moves at +0.7º/day in System I (–6.66º/day in System III). Diagonal lines indicate L1= 0. (In all figures with drift charts, longitude increases to the right and time increases downwards, marked in months.)
For a full-resolution version of the whole chart, see Supplementary Online Figure 2: **http://www.britastro.org/jupiter/SED-paper_SOM.pdf**

In this paper we address the observed dynamics of the SED and its relationship to the SEBn jet. We have previously shown that, in 1999/2000 and 2000/2001, drift rates of visible spots tended to increase with longitude east of (preceding) the SED.[1,2,17] Here we show that these drift rates represent the same speeds observed by the *Cassini* spacecraft, and in subsequent years, we find speeds similar to those previously reported for the peak speed of the jet. Thus, it appears that we are observing the true speed of the jet at cloud-top level. We show that there are systematic variations according to the state of the SED:

1) In years when the SED is clearly visible, it systematically perturbs the speeds observed all around the SEBn jet.
2) In other years, when the SED is obscure, it can still be tracked, but it no longer modulates the observed speeds in the SEBn jet.
3) Different speeds can coexist in the SEBn jet, which are best explained by weather systems arising at variable depths within it.

Table 1. Speed of the SEBn jet: Global averages from spacecraft images

	Ref.	*Lat. (°S)*	*<u>(m/s)***
***Voyager* 1979**	4*	7	150
	5	7.0	128
	6	7.2	160
	7	7	150
	8	6.8	150
***HST* 1994-1998**	7	7	150
	9	7	152
	10	7.2	155
***Cassini* 2000**	11	7	137
	12	7	142

Lat., planetographic latitude; <*u*>, mean peak jet speed in System III.
* *Voyager* measurements: The initial charts of speeds from *Voyager 1* images[3,4] showed a peak speed for the SEBn of ~160m/s (west of the SED) and ~150 and 145m/s (in other longitude ranges). Although the exact positions relative to the SED were not stated, it is possible that the differences were due to longitudinal variation as reported herein. These measurements 'referred to the chevron-shaped features that propagate along the boundary'.[4]
**Uncertainties of ±9m/s were stated in references 5 and 10. Similar uncertainties are likely to apply to the other values quoted here. In many cases the mean values were read off published charts.

Observations and analysis

All data are from amateur observers with telescopes of apertures 200–410mm, using CCD cameras or webcams. The

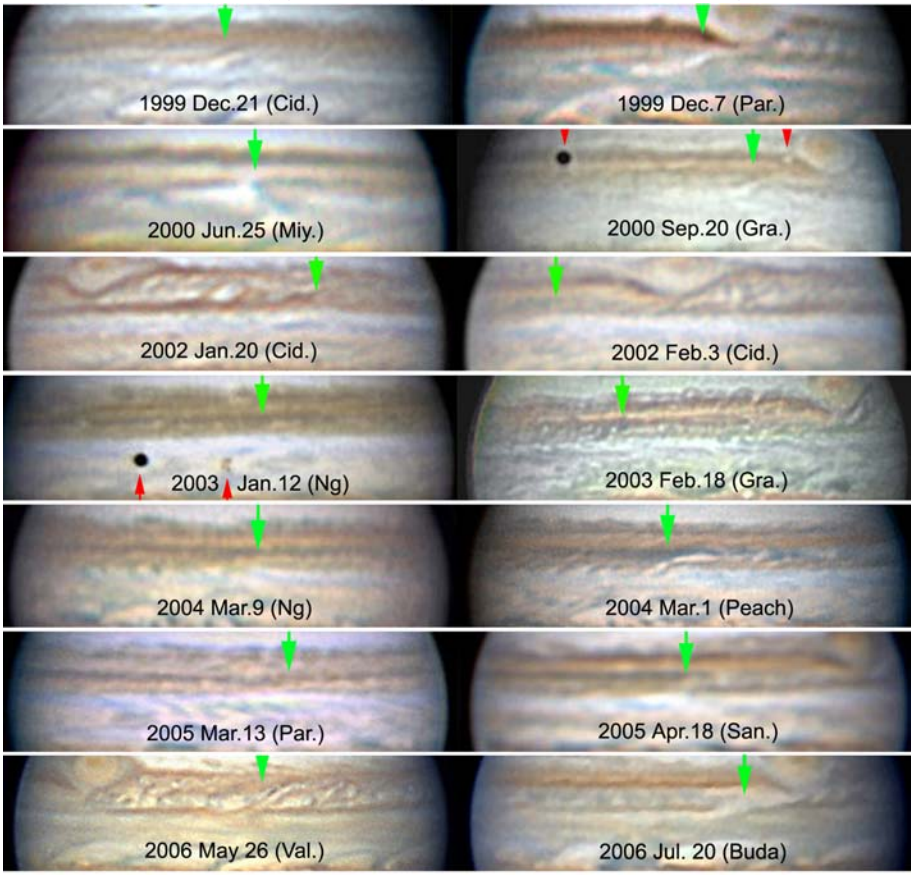

Figure 3. Typical views of the SED, 1999–2006.
Each panel covers approximately 25ºS to 8ºN. South is up. For each apparition, the left image shows the SED when it was remote from or west of the GRS; the right image shows it east of the GRS, *i.e.* just after passing it, when the SED rift tends to be most well-defined. Green arrow indicates longitude of the SED (main complex). In 1999 and 2000 it was clearly defined by a bright rift in SEBn, surrounded by blue-grey shadings. This aspect returned in 2004. In contrast, in 2002, 2003, and 2005, the SED was marked mainly by a bright strip in EZ(S) with a dark blue streak along its north edge, although there was usually still a small discontinuity in SEBn at the west end of these strips. In 2006, the SED was marked by one of several diffuse brownish shadings accumulating in the EZ(S). Red arrowheads indicate Io and its shadow in transit. Observers' names are abbreviated: see text for full names.

names of the observers and details of their equipment are given in our regular reports in this *Journal*. The observers whose images are shown in the figures (where their names are abbreviated) are as follows: Stefan Buda (Australia); Antonio Cidadão (Portugal); Christopher Go (Philippines); Ed Grafton (Texas); Jason Hatton (California); Isao Miyazaki (Japan); Eric Ng (Hong Kong); Donald C. Parker (Florida); Damian Peach (Tenerife and Barbados); Jesus R. Sanchez (Spain); Maurice Valimberti (Australia).

The number and resolution of available good images has greatly improved in the last few years, particularly from 2002 onwards, due to the widespread use of affordable webcams. Their high sensitivity and speed allow hundreds of images to be recorded within about one minute, with very short exposures.[18] Software, most commonly *Registax*, is then used to select, align, and sum the images that contain sufficient data at high spatial frequencies, thus overcoming the effects of atmospheric turbulence.[19] Further processing can then be applied to enhance and sharpen the resulting image. This 'webcam revolution' has greatly expanded our ability to track the tiny features on SEBn which reveal the peak speed of the jet.

The other innovation that has improved the quality of amateur Jupiter studies is the digitisation of measurements, using the *PC-/WinJUPOS* program **(http://jupos.org)**.[20] Some of the longitudes in 1999/2000 were measured manually from pairs of images as previously described.[1] Otherwise, all longitudes and latitudes have been measured using *PC-/WinJUPOS*, by G. Adamoli, M. Jacquesson, H.–J. Mettig, D. Peach and M. Vedovato.

Drift rates in System I (DL1, in degrees per 30 days) are converted to eastward wind speeds in System III (u, in m/s), assuming planetographic latitude 7.2ºS (see footnote to Table 2). (A latitude shift of 1º higher or lower would change the computed wind speed by ~0.25 m/s.) Drifts in longitude are typically accurate to ± ~2–6º/month (1–3 m/s) for single short-lived spots, which are tracked for between 4d and 15d, and to ≤2º/month (1 m/s) for features that last more than a month.

Latitude measurements typically show a standard deviation of ~0.4º to 0.6º. The means for different spots on SEBn are not significantly different, showing a standard deviation of ≤0.15º within the apparitions of 2004 and 2005. Latitudes are planetographic. In all images in this paper, south is up and longitude increases to the right (following or western side).

Results

Longevity of the SED

Charts showing the motion of the SED in 1999/2001 have already been published.[1,2] Here we show that the SED has continued to exist up to 2006. It has always been most consistently tracked as a boundary between disturbed and quiet sectors of the SEBn/EZ(S). This is shown in Figure 2, which is a longitude-v.-time chart for all the small dark spots that we have measured from late 1999 to early 2006 in this latitude band (5–8ºS). The ensemble of spots clearly defines a boundary, traced continuously from 1999 to 2006**,** and this coincides with the SED. On its east side there are numerous small spots (which usually move much more rapidly than the SED itself, as shown below), while on its west side there is a gap in the distribution of spots. The presence of this boundary on the chart has revealed the SED even when the actual structure at this longitude was obscure.

Figure 3 shows typical aspects of the SED in each apparition since its first appearance. The most consistent fea-

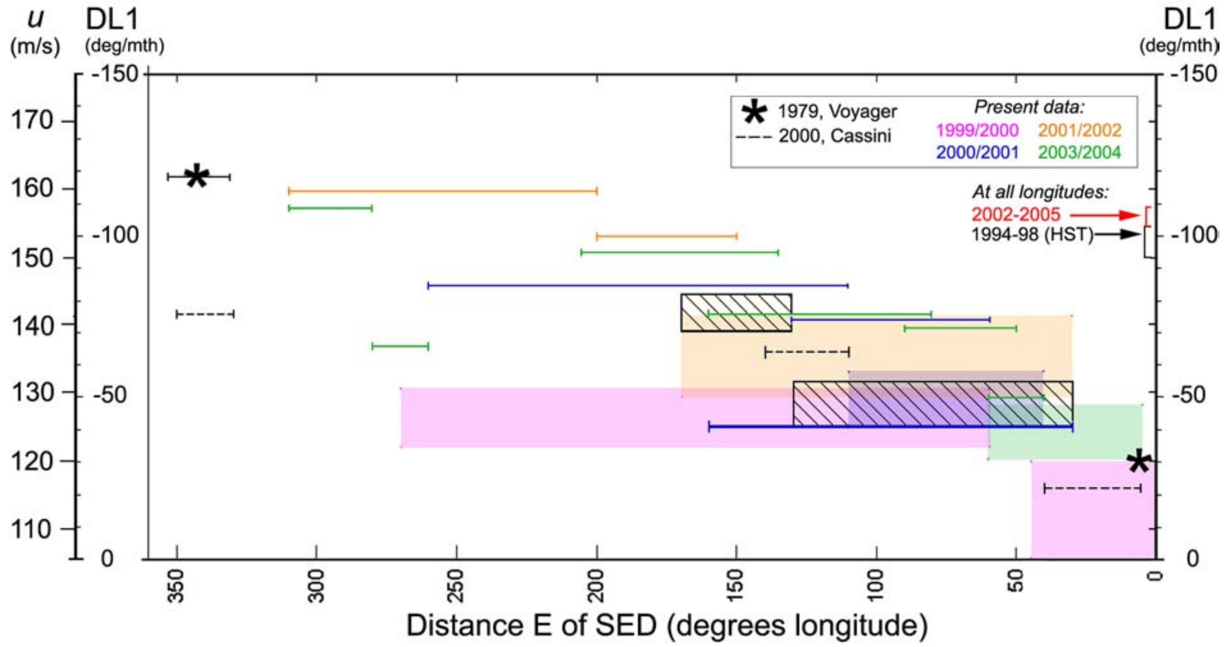

Figure 4. Speeds of spots on SEBn in relation to the SED.
The observed speeds of small spots on SEBn, at ~7ºS, are plotted against the distance preceding (east of) the SED (main complex). Data are from Table 2. Shaded boxes represent the range of speeds and longitudes for numerous spots; single horizontal lines represent tracks of one or a few spots, which travel from right to left. Individual spots were rarely seen to accelerate, so all have been plotted for constant speed. Our measurements are colour-coded by apparition (see box on figure). The dotted lines and the cross-hatched box are measurements from *Cassini* strip-maps such as those in Figure 5. The asterisks are values from *Voyager*.[6]

ture is a discontinuity on the SEBn, which is sometimes a bright 'rift', but it is often merely a boundary between sectors of the belt with different albedo, or a slight deviation of the SEBn edge. It was often conspicuous in 1999 and 2000 and again in 2003/'04.

When the SEBn feature is inconspicuous, there is usually a persistent feature in the EZ(S) at the same longitude, as shown by charts for streaks at 3–6ºS (Figures 1b, 2b, 3). This is the west end of a bluish-grey streak, which is superficially no different from other, transient streaks in the EZ(S), but is revealed by the charts to be a persistent feature of the SED, forming the northern boundary of a very bright white strip of EZ(S).

The continuous existence of the SED is thus established by:

1) Direct tracking of the main complex in 1999–2002,[1,2] and 2003/'04 (see below).

2) Direct tracking of the EZ(S) bluish-grey streak in 2002, 2003, and 2005 (Figure 2b).

3) The boundary between dense and sparse regions of spots on SEBn, throughout the whole period (Figure 2a).

The drift rate of the SED within each apparition is listed in Table 2. Its speed in System III has varied from 88–90 m/s in its early years to 93–94 m/s more recently.

Pattern of wind speeds in relation to the SED

To study the drift rates of spots which may represent the SEBn jet, we again use positional measurements of small spots within latitudes 5–8ºS from ground-based images, plotted on larger scales. Individual dark and bright spots are tracked for between 4 and 15 days, as shown in detail below, and the fastest speeds shown by these spots, in the hemisphere west of the SED, agree well with speeds observed by HST or *Cassini* for the peak of the jet (Table 1). We now show that even the slower speeds shown by some of these spots are neither random nor latitude-dependent, but represent systematic variation of the observed jet-speed in relation to the SED.

The small dark spots that display these drift rates appear to be similar in type and latitude at all longitudes, and are identified with the chevrons familiar from spacecraft images. They appear as tiny dark bluish-grey spots or projections on SEBn, at latitude 7.26ºS (±0.23º; see Table 2), sometimes with a tenuous curving extension into EZ(S). There are also small bright spots which lie at ~6.5ºS (±0.4º), between the dark ones, and move with them.

Table 2, available online, lists all our measurements of drift rates for these spots, and they are also plotted in Figure 4 as a function of longitude east of the SED, with each apparition shown in a different colour. The main result is that, in most years, drift rates were systematically lower to the east of the SED.

Individual spots were rarely seen to accelerate, even when they were tracked for many tens of degrees longitude. Instead, they tended to retain their initial speed. Figure 4 suggests that this initial speed may have been a rather well-correlated func-

Table 2. Speeds of SEBn features, 1999–2005

This table lists the observed drift rates for the SED main complex, and for small spots on SEBn in each longitude sector, for each apparition from 1999 to 2005, and for *Voyager* (1979) and *Cassini* (2000). The drift rates for the small spots are all plotted in Figure 4. Latitudes and uncertainties are also tabulated.

This table is presented as Supplementary On-line Material: **http://www.britastro.org/jupiter/SED-paper_SOM.pdf**

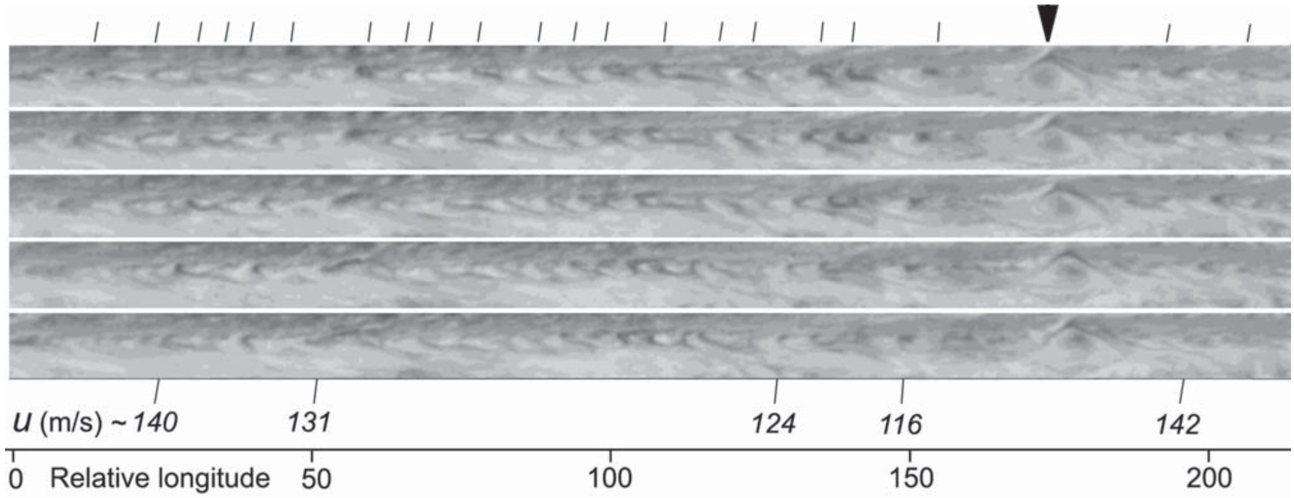

Figure 5. Strip-maps from the *Cassini* imaging system in near-infrared (2000 Oct–Nov), realigned in a longitude system with a rate close to System I. Five strip-maps are shown (from a much longer series), taken at 20-hour intervals. They cover the SEBn (above) and EZ(S) (below), and were aligned on the longitude of a long-lived NEBs projection so that the SED main complex (arrowhead) shows only a slow increase in longitude. The features tracked are the dark chevrons (< shapes), indicated by lines above. Drift rates estimated for some examples are shown below. South is up, longitude increases to the right (arbitrary scale), and time increases downwards. These are frames from the *Cassini* movie of cylindrical projection maps at 756nm.[21] *(originals from NASA/JPL/Southwest Research Institute)*.

tion of longitude, although the observations are not complete enough to establish this with much precision.

It is important to note that there is no evidence for variations in latitude of these dark spots. Any spread of mean latitudes is attributable to extension of the spots themselves, or possibly to variation of the albedo boundary of the SEBn. Taking the means and standard deviations of latitudes for individual dark spots from Table 2, they are all at the same latitude: 7.26ºS ±0.23º (overall), 7.30ºS ±0.14º (2004), 7.20ºS ±0.09º (2005). This is indistinguishable from the jet peak position observed from spacecraft (Table 1). Even if the latitudes differed from the jet peak by 0.5º to north or south, spacecraft profiles of the jet[5–12] would predict a reduction in speed of no more than 10 m/s, much less than the speed differences which we report here.

Our measurements for 1999/2000 and 2000/2001 have already been published.[1,2,17] In order to test whether these represented the peak speed of the jet, not only in the most rapid sector but also in the apparently slower sector east of the SED, we have inspected contemporaneous strip-maps from a *Cassini* planisphere movie.[21] Maps from this movie, covering about three weeks in late 2000, were re-aligned in System I to display motions in the equatorial jets (*e.g.* Figure 5). These maps were made from images at 756nm (I-band continuum), a channel in which the atmosphere is transparent down to >30 bars in the absence of any clouds or haze.[22] These strip-maps showed small dark projections or chevrons all round the SEBn, which were evidently the same type of feature that we were tracking, and they clearly dominated the velocity field of the SEBn jet. They looked the same whether east or west of the SED; any differences in latitude were less than the sizes of the features themselves. Many had lifetimes ranging from 7 to >16 days, and for these we measured their drift rates over these intervals on the maps. The longitude scale was established by internal reference to long-lived features such as the SED (main complex), the Great Red Spot, and NEBs dark projections, whose drift rates were known accurately from ground-based observations.[17]

The derived drift rates were 125–132 m/s for most of the chevrons east of the SED, and 139–145 m/s remote from and west of the SED (Table 2). Both values agree well with our ground-based measurements, and the latter value agrees well with the published jet profiles from the *Cassini* data. These show a mean speed for the SEBn jet of ~137 m/s (from autocorrelation)[11] or 142 m/s (from feature tracking).[12] Thus, our ground-based measurements are detecting the same wind speed as the *Cassini* imagery.

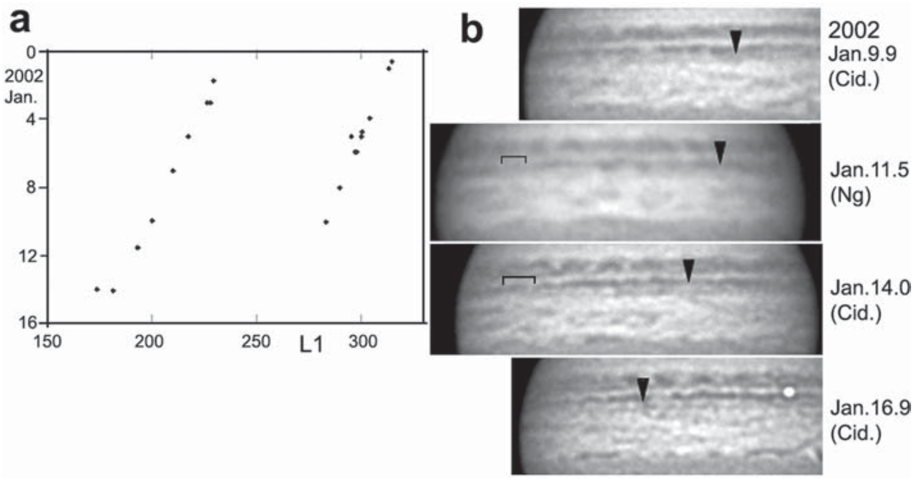

Figure 6. Data in 2001/02.
(a) Longitude chart of the fastest dark spots in the SEBn jet at 7ºS.
(b) Images showing the fastest spot on SEBn (arrowhead) approaching the SED main complex (bracket). The images are aligned on a dark plateau on NEBs to show the very rapid motion. 2002 Jan 9, 22:18 UT, CM1=190; Jan 11, 12:49 UT, CM1=159; Jan 13/14, 00:05 UT, CM1=167; Jan 16, 21:36 UT, CM1=190.5. All images by A. Cidadão (Portugal) except Jan 11 which is by E. Ng (Hong Kong). All images in red light except Jan 16 which is in near-infrared (>830nm).

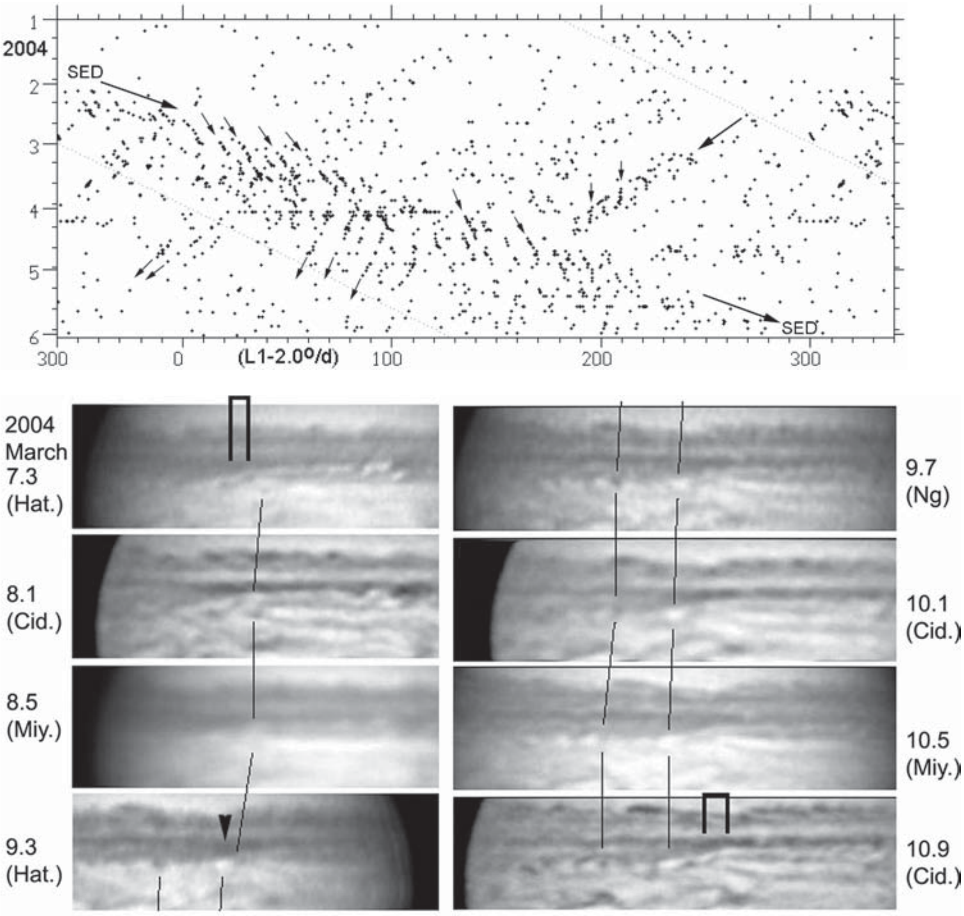

Figure 7. Data in 2004.
(a) *(top)*. Longitude chart of dark spots at latitudes 5.0 to 8.0ºS. Time scale is marked in months. Longitude scale moves at –2.0º/day in System I. Diagonal dotted line indicates L1=0. Small arrows indicate many of the individual spots. Large arrows indicate the main complex ('SED', downwards to right) and the rapidly-moving band (downwards to left).
(b) *(bottom)*. Images showing the motions in and around the SED in detail, at intervals of 1–2 jovian rotations, in 2004 March. The images are aligned in System I. The SED main complex (brackets on first and last images) retrogrades at ~+0.8º/day. Lines track some of the small spots with more rapid motions, prograding at ~–1.2 to –1.3º/day: first, one of two small dark spots crossing the mouth of the rift; then, a bright spot which appears at the same location (arrowhead); and preceding it (to the left/east), a dark spot which is preceded by a chain of dark and bright spots, all drifting at similar speed. Each image is the sum of red and green channels from a colour image, except for March 8.1, 10.1, and 10.9, which are near-infrared images.
Images were taken as follows: 2004 March 7, 06:28 UT, CM1=131, Hatton; Mar 8, 02:18 UT, CM1=137, Cidadão; Mar 8, 12:07 UT, CM1=136, Miyazaki; Mar 9, 06:38 UT, CM1=93, Hatton; Mar 9, 16:55 UT, CM1=109, E. Ng; Mar 10, 03:01 UT, CM1=119, Cidadão; Mar 10, 12:29 UT, CM1=105, Miyazaki; Mar 10, 22:34 UT, CM1=114, Cidadão.

In late 2001, the SED remained feebly and intermittently visible**,** though it was little more than a discontinuity between sectors of SEB(N).[23] In 2002 January even this ceased to be detectable. However, inspection of the *JUPOS* charts revealed that a dark streak in EZ with a uniquely slow drift, forming the northern boundary of a very bright white strip in EZ(S), still marked the SED. From 30º to 170º east of it, the many tiny projections separated by tiny bright bays could be tracked at ~134 m/s, over short intervals.[2,23] Further east there were even faster spots. The fastest speed was 160 m/s, for a small bluish-grey projection, tracked until it was only 50º west of the SED **(**Figure 6).

In 2002/'03, the SED was not noticed as a visible feature, and was even thought to have disappeared; only in retrospect was it shown to be still present in the *JUPOS* chart (Figure 2). Nor was there any variation in speed with longitude. Instead, the chart was dominated by tracks moving at 154–158 m/s: at least seven such tracks, for tiny spots both bright and dark, at all longitudes. Some spots individually moved with this speed, whereas other tracks on the chart were broader and probably represented loci of disturbance rather than single spots.

In early 2004, the SED reappeared visibly, and speeds of tiny spots on SEBn again varied according to their longitude (Figure 7a). Hi-res images (Figure 7b) showed them appearing at the east end of the rift in the main complex. A few spots seemed to accelerate although many had fixed speeds as usual. But there was also a band of disturbance moving at 155 m/s which went all around the planet relative to the SED (see next section).

In the *Voyager* data in 1979, it appears that there was a similar longitude-dependence of speed relative to the SED (the Great White Spot). The one study of *Voyager* data which sampled specific locations around the GWS itself was by Maxworthy,[6] who found a peak of 162 m/s west of the SED (features at 6 to 7.5ºS), but 120 m/s east of it (features at 7.5 to 9ºS). Although the latter values could be lower due to absence of trackable features in the latitude of the jet peak, their agreement with our recent data suggests that they did indeed represent variation of speed with longitude, and this would explain the discrepancies between different reports of the mean speed from *Voyager* data (Table 1). These values are shown by large asterisks in Figure 4, and agree well with the range that we have recorded in 1999–2004.

Coexistence of different speeds unrelated to the SED

In 2002/'03, as noted above, the SED produced almost no visible disturbance, and no variation of speed with longitude. Instead, the chart was dominated by tracks moving at 154–158 m/s: *i.e.* virtually the maximum known speed of the jet, at all longitudes. This shows that the SED can continue to exist even if it does not perturb the drift rates of the visible spots in the jet. But within these fast-moving bands, short tracks of data points suggested that several individual dark spots drifted at ~131–139 m/s over intervals of a few days. This dual speed behaviour would be better defined in the next two apparitions.

In early 2004, while the SED had revived as noted above, there was also at least one persistent band of disturbance moving at 155 m/s, which completely circumnavigated the planet relative to the SED. Within this locus, a pair of spots moved with 137 m/s (Figure 7a). This shows that a disturbance moving with the full jet speed can coexist not only with the SED (their tracks intersected), but also with individual spots moving more slowly (the slow-moving spots were among those which, as an ensemble, defined the fast-moving band).

In early 2005, with the SED again quiescent, this phenomenon was repeated on a much larger scale. There were several bands of activity on SEBn with 155 m/s, and within them, many individual spots moved with a mean of 133 (±3) m/s. All these speeds again referred to tiny dark spots or projections at 7.2ºS, with a few bright spots between them at 6.7ºS (Figure 8).

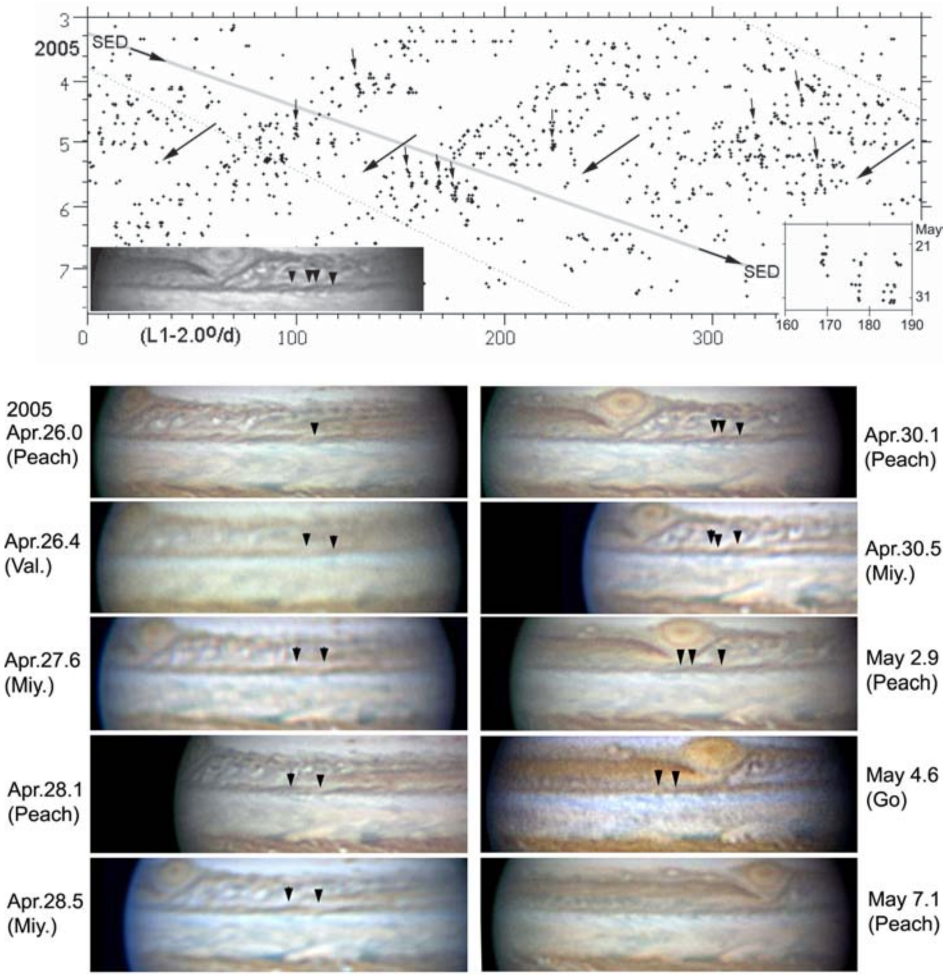

Figure 8. Data in 2005.
(a) *(top)*. Longitude chart of dark spots at latitudes 5.0 to 8.0ºS. Time scale is marked in months. Longitude scale moves at –2.0º/day in System I. Diagonal lines indicate L1=0 (dotted line) and the track of the SED (grey line). Note several rapidly-moving bands (diagonal down to the left: DL1 = –3.5º/day; 155 m/s; large arrows indicate gaps between them), but the individual spots in them move more slowly (near-vertical tracks, indicated by small arrows: 128–136 m/s). Inset at right shows three such tracks at expanded scale. Inset at left shows one such cluster of chevrons on 2005 April 30 (D. Peach: red + green channels).
(b) *(bottom)*. A series of these strip-maps in colour showing the motion of the cluster at ~–2.6 to –2.0º/day, within a band of activity that was moving at ~–3.5º/day.

Discussion

Structure, longevity, and dynamics of the SED

These observations reveal the only known example of systematic longitudinal variation in the speed of a prograde (eastward) jet on Jupiter. These speed variations, for the chevrons in the SEBn jet, are likely to be clues to understanding two interlocking issues: the nature of the SED, and the structure of the SEBn jet within which it is embedded.

The SED affects many aspects of the SEBn/EZ(S) while moving at a much slower speed than the bulk flow of the jet, and thus appears to represent a solitary wave that retrogrades with respect to the jet.[1,2,6] The nature of the wave is not yet certain. Observationally, it is manifested in various patterns, whose relative prominence has varied during its lifetime: patterns of albedo (the stormy sector and features in EZ(S)), of high-altitude haze (the pattern seen in methane bands), of belt structure (the rift), of small-scale disturbance (the chevron distributions), and of drift rates. The present results show that the most persistent, and presumably fundamental, aspects relate to the structure of the SEBn and EZ(S). The discontinuity in SEBn is the main visible defining feature. The anticyclonic circulation at that point is observable only by hi-res spacecraft imaging, but may well be persistent as it would couple the visible discontinuity in SEBn to the visible bright strip and blue streak in EZ(S), which are also persistent features. The other aspects of the SED may derive from this local disturbance at times when it is most vigorous.

The SED was most prominent in 1999–2001, but the present results show that it has persisted at least until 2006. This is another similarity to the SED that was observed as a Great White Spot by *Voyager* in 1979. That one was prominent from 1976 to 1981, but persisted until 1989 as a discontinuity in the SEBn.[15] It is now clear that, despite their different albedo patterns, the SEDs of 1976–1989 and 1999–2006 were very similar phenomena.

The ground-based and spacecraft data now give a consistent picture of the behaviour of the SEBn jet in years when the SED is conspicuous. In Figure 4, the gradient of speed with longitude is shown for all the relevant years. Overall, there is a progressive increase in speed from ~120 m/s just east of the SED to the maximum speed about half way round the zone. It seems that the maximum speed was slower when the SED was strongest, in 2000/'01 (141–146 m/s, as also observed by *Cassini*). (In 1999/2000, as our observations had not yet attained the present resolution, it is possible that the maximum speed was not observed.) In 2001/'02 and 2003/'04 when the SED was weaker, and also in 1979, the maximum speed rose to 155–162 m/s. Finally in 2002/3 and 2005, years when the SED was weakest, there was no speed gradient at all, and the maximum speed was 155–158 m/s at all longitudes, similar to the value recorded by HST images when the SED was absent.

The reason for the variation in strength of the SED is unknown, but it may be connected with the activity of 'rifts' (bright divergent cloud systems) in the adjacent SEB. The mid-SEB rifts arise from thunderstorms driven by moist convection from a deep cloud level, and they transduce energy from moist convection into wind systems.[22,24] The main complex of the SED is often reinvigorated as it passes the perennial rifts northwest of the GRS, and it has been proposed that this interaction may sustain the SED.[4,13,14] Every few years, rifts also break out within the SEB at a longitude remote from the GRS. Since the SED appeared, such mid-SEB outbreaks began in summer 2003 and in late 2005. The revivals of the SED in spring 2004 and in mid-2006 both occurred in the late stages of these outbreaks, when the resulting turbulence was channelled close to the SEBn, suggesting that the mid-SEB outbreaks may have supplied energy to reinvigorate the SED.

Discussion of the physical basis of the SED has so far centred on its similarity to the more familiar disturbances on the corresponding jet at 7ºN, on the North Equatorial Belt south edge (NEBs).[1,2,6] These NEBs features are called dark projections from their appearance at visible wavelengths and 5-micron hot spots from their thermal infrared emission.[25,26] They often resemble the SED in having a rift at the east end, and at least sometimes, partial anticyclonic circulation to the south.[8] Like the SED, they are large coherent disturbances embedded in a much faster jet, although the great rapidity of the NEBs jet (~170 m/s) is not seen at cloud-top level, but only deeper as sensed by the *Galileo* probe[27] and *Cassini* infrared imaging.[28] Allison[16] proposed that they are trapped Rossby waves. Rossby waves are horizontal meanderings of a jet, governed by the variation in the Coriolis effect with latitude. This model required that the speed of the waves (phase speed) was much less than the wind speed of the jet, and this prediction was validated by the *Galileo* probe's results. This model has been reinforced by subsequent theoretical studies.[26,29-31] The phase speed should be a function of the wavelength. Evidence for such a correlation was reported,[26] and more thoroughly confirmed by Arregi *et al*.[32] Our data for recent years are consistent with theirs, and also extend the range of the correlation.[23]

The SED in the *Voyager* era was suggested to be a similar trapped Rossby wave with the largest possible wavelength, its slower drift rate being consistent with the correlation proposed for the NEBs.[6,16] To develop this model for the SED, our results indicate that it will be necessary to match both the anticyclonic circulation and the long-range modulation of the observed jet speed. Rossby wave models for the NEBs projections can produce adjacent anticyclonic circulation[30] or asymmetrical modulation of the jet speed,[31] but not yet both in the same model, so further exploration of the parameters may be worthwhile. Our results further suggest the possibility that the NEBs jet speed might likewise vary east and west of the NEBs projections, and this might be detectable by closer examination of the *Cassini* 756nm imagery.

Variations of speed in the SEBn jet

We have shown that the small chevrons on the SEBn show multiple speeds, with characteristic patterns at different times:

1) When the SED is clearly visible, the speeds observed in the jet vary systematically with longitude relative to the SED;
2) When the SED is obscure, long-lived bands of disturbance propagate at full jet speed (155 m/s), but individual chevrons within them move more slowly (128–139 m/s) over short intervals.

Each of these alternative situations has also been scrutinised by spacecraft. *Voyager* and *Cassini* viewed the region when a strong SED was present, and the systematic variation of speeds with longitude is consistent with their data. HST and *Galileo* viewed the planet when no SED was detectable (at least, there was none strong enough to be clearly visible nor to perturb the jet speed), and the consistent speed recorded no doubt represents the undisturbed speed of the jet.

There have been no detailed models of the SEBn jet, and here we merely outline two possible theoretical scenarios. In the first, the chevrons are waves, with variable phase speeds that are all less than the true peak jet speed. In the second, the chevrons do indeed trace the physical wind speed, perhaps at variable depth.

The hypothesis that the chevrons are waves was proposed by Allison:[16] he speculated that they might be the shortest-wavelength member of the family of equatorial trapped Rossby waves. They do resemble the NEBs dark projections in miniature. Shorter-wavelength Rossby waves would have faster drift rates in System III, other parameters being equal. Thus the true peak jet speed on SEBn would be faster than any drift rates yet observed, possibly ~170–180 m/s as in the other two fastest jets on the planet, *viz*. the NEBs (at depth) and NTBs (23.5ºN, at cloud-top level during certain epochs). This model cannot be ruled out at present. The variable speeds reported here could be accommodated as variable phase speeds, even without variation in wavelength, by varying the effective depth of the waveguide layer.[26,32]

However, this hypothesis has several difficulties. It is not clear how the concurrent dual speeds reported here could be accommodated. The bands of activity moving at 155 m/s do not have the visible characteristics of features proposed to be Rossby waves, and yet they move at the same speed as the faster chevrons, suggesting that this is indeed the peak wind speed. The wave model also does not account for the detailed shapes of the chevrons in spacecraft images. Their shapes suggest that they are real cloud features, moulded by the wind speed gradients; and the observed latitudinal wind profiles (references in Table 1) show a smooth peak suggesting that this really is the true peak wind speed at cloud-top level.

The alternative is that the chevrons do trace the real wind speed. In that case, multiple speeds could be accommodated by disturbances arising at different depths. The NEBs jet speed increases with depth,[27] and theoretical studies suggest that other jet speeds also increase with depth, as vertical velocity gradients permit modelling of observed patterns of jets and dynamical interactions.[30,33,34] If there is a similar gradient in the SEBn, the slower-moving chevrons could indeed trace the wind speed at cloud-top level, while the bands of disturbance moving at 155 m/s could represent disturbances in the faster jet below the cloud tops. In relation to the active SED, the longitudinal variation of speeds might represent a range of depths at which small-scale disturbances were triggered, and/or a real variation in cloud-top wind speed.

More detailed longitude-resolved measurements on images at different wavelengths from *Voyager* and *Cassini* might give further information on these issues, and could be compared with the hi-res study performed from the *Galileo Orbiter* in the absence of an SED.[8] Further study of these phenomena could give insight into the essential third dimension of jovian jet dynamics.

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Note added in proof:

Since this paper was completed, the SED has again been a conspicuous feature in the apparitions of 2006, 2007 and 2008. Details can be found in interim reports on our website: **http://www.britastro.com/jupiter/section_reports.htm**.

Results on tracking the SEBn jet can be summarised as follows:

- In 2006, SEBn jet speeds could not be obtained because of widespread shading at this latitude.
- In 2007, speeds were determined for many chevrons and were largely consistent with the gradient measured in 2000; however there were also exceptionally variable speeds east of the SED. Thus the speeds ranged from 126–141m/s at most longitudes, but reached ~145m/s west of the SED.
- In 2008, the chevrons are especially distinct and their speeds very clearly reproduce the gradient that we report herein for 2000, from 118m/s east of the SED to 140m/s west of the SED.

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