

Longitudinal Variation and Waves in Jupiter's South Equatorial Wind Jet

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1 **Abstract**

2 A detailed study of the chevron-shaped dark spots on the strong southern equatorial wind
3 jet near 7.5° S planetographic latitude shows variations in velocity with longitude and
4 time. The presence of the large anticyclonic South Equatorial Disturbance (SED) has a
5 profound effect on the chevron velocity, causing slower velocities to its east and
6 accelerations over distance from the disturbance. The chevrons move with velocities
7 near the maximum wind jet velocity of ~ 140 m/s, as deduced by the history of velocities
8 at this latitude and the magnitude of the symmetric wind jet near 7° N latitude. Their
9 repetitive nature is consistent with a gravity-inertia wave ($n = 75$ to 100) with phase
10 speed up to 25 m/s, relative to the local flow, but the identity of this wave mode is not
11 well constrained. However, for the first time, high spatial resolution movies from Cassini
12 images show that the chevrons oscillate in latitude with a 6.7 ± 0.7 -day period. This
13 oscillating motion has a wavelength of $\sim 20^{\circ}$ and a speed of 101 ± 3 m/s, following a
14 pattern similar to that seen in the Rossby wave plumes of the North Equatorial Zone, and
15 possibly reinforced by it. All dates show chevron latitude variability, but it is unclear if
16 this larger wave is present during other epochs, as there are no other suitable time series
17 movies that fully delineate it. In the presence of multiple wave modes, the difference in
18 dominant cloud appearance between 7° N and 7.5° S is likely due to the presence of the
19 Great Red Spot, either through changes in stratification and stability or by acting as a
20 wave boundary.
21

1. Introduction

Many previous works (*e.g.*, Ingersoll et al. 1979, Mitchell et al. 1979, Limaye 1986, Simon-Miller and Gierasch 2010, Garcia-Melendo et al. 2011) have discussed Jupiter’s zonal wind flow as measured from spacecraft imaging data. These works included the study of the stability of the average zonal wind profile, explanations of its magnitude and asymmetries, and searches for temporal periodicities. In particular, the equatorial wind jets at $\sim 7^\circ$ N and S planetographic latitude are interesting because wave activity has been used to explain the visible cloud structure, wind asymmetry/variability, and even the unexpected results of the Galileo probe (Atkinson et al. 1997, 1998).

For example, at 7° N, Rossby waves have long been suspected of playing a role in formation of the regular arrays of bright cloud plumes and intervening holes in the clouds, interpreted as dry downdrafts (Allison 1990, Dowling 1995, Moreno et al. 1997, Showman and Dowling 2000, Friedson 2005, Garcia-Melendo et al. 2011). The NEZ pattern of plumes have a velocity of 100-110 m/s relative to System III longitude, with faster features up to 150 m/s, approaching the wind jet velocity confirmed at depth by the Galileo probe (Atkinson et al. 1997, 1998, Garcia-Melendo et al. 2011). The number, shape, and velocities of the plumes can vary, but in the modern spacecraft era, there has been little temporal change to the visible structure at this latitude, dominated by large plumes (*c.f.*, Mitchell et al. 1979, Garcia-Melendo et al. 2011).

At 7.5° S, the usual small cloud features visually appear chevron-shaped and periodic in nature, as seen in Figure 1. Allison (1990) attributed these features to possible gravity-inertia waves, and Garcia-Melendo et al. (2011) briefly considered a high wavenumber Rossby wave to explain variations in their velocity. However, in addition to the smaller cloud features, a large feature, known as the White Spot or, more generally, the South Equatorial Disturbance (SED) is sometimes present within this flow field, extending from close to the equator, across the 7.5° S boundary and often interacting into the South Equatorial Belt (SEB) (*e.g.*, Rogers 1995, Beebe et al. 1989, Rogers et al. 2005). It often has a plume-like structure, similar to the NEZ plumes, and has been proposed as a solitary wave feature, as well (*e.g.*, Maxworthy 1985, Allison 1990, and others).

In general, large stable features are vortices, such as the Great Red Spot (GRS), and are known to block or deflect the average zonal flow, to have internal rotation, and to drift at a rate slower than the zonal flow. This is the case for the SED as well, with internal anticyclonic motion of ~ 20 to 40 m/s near its periphery seen in Voyager and Cassini images (Beebe et al. 1989, Rogers et al. 2005, Garcia-Melendo et al. 2011). Throughout this work, we will refer to the main cloud feature as the SED, and any separate secondary bright structures as plumes.

The reported zonal velocity of the 7.5° S wind jet, based on correlations and measurements of chevrons and white clouds, varies from 130 to 160 m/s depending on method and dataset (*e.g.*, Limaye 1986, Vasavada 1998, Simon-Miller et al. 2007, Simon-Miller and Gierasch 2010, and many others). However, there are also longitudinal variations in the speed of this wind jet, as traced by the motions of the chevrons (Rogers and Mettig 2008). In the absence of an active SED, the maximum feature velocity is

1 observed all around the planet, but some individual features move more slowly over
2 shorter intervals. However, when the SED is conspicuous, the speed of the features are
3 markedly reduced east of the SED and sometimes, to a variable extent, at all longitudes
4 (Rogers and Mettig 2008).

5
6 In this paper, we use high spatial resolution Voyager, Hubble, and Cassini data,
7 combined with a time series of ground-based data, to examine and characterize
8 longitudinal variations within the flow field at 7.5° S. Section 2 discusses the general
9 appearance of Jupiter's equatorial region and the South Equatorial Zone (SEZ) to SEB
10 interface. This includes the formation, cloud structure and internal flow, and evolution of
11 the latest SED and the morphology and spacing of chevrons. In Section 3 we show
12 chevron velocities and latitudes and the SED's effect on cloud velocity at nearby
13 longitudes. Section 4 explains the more detailed and complex chevron motions revealed
14 in time-lapse movies. Finally, in Section 5 we examine the identity of wave features and
15 causes for the chevron pattern, as well as the asymmetry seen across the equatorial
16 clouds.

17 **2. Appearance of the South Equatorial Zone and Belt Interface**

18 The Equatorial Zone (EZ) is often filled with white clouds, with small, chevron-shaped,
19 clouds on the southern edge. These features mark the boundary of the EZ from the SEB
20 and correspond with the peak of a strong eastward wind jet. During the Voyager and
21 Cassini flyby eras, there was a single large cloud feature in the SEZ, the SED. Figure 1
22 shows a Cassini map of Jupiter with these features labeled. In the absence of an SED,
23 chevrons encircle the entire planet, though sometimes with areas of less distinct features.
24 Strip maps for various dates where full global coverage was obtained, are shown in
25 Supplemental Online Figure S1, for ease of viewing. Table 1 outlines the spacecraft data
26 used in the subsequent analysis, and ground-based data are available over the entire time
27 period to supplement spacecraft views.

28 **2.1 History, Motion, and Morphology of the SED**

29
30 The SED is a variable feature, and is not present at all times. It was apparent during the
31 Cassini flyby in 2000/2001, as seen in Fig. 1, but was most dramatically visible during
32 the global upheaval in 2007, as seen during the New Horizons flyby. In this era, clearing
33 of the equatorial white clouds made the SED prominent at visible wavelengths,
34 temporarily taking on a double appearance, as seen in Fig. S1. Similarly, during the
35 Voyager 1 and 2 flybys in 1979, the equator was nearly cloud free and the SED
36 prominent (Smith et al. 1979a, 1979b, Sanchez-Lavega and Rodrigo 1985, Beebe et al
37 1989, Rogers 1995). The Voyager SED lasted about 12 years from 1976 to 1989 (Rogers
38 1995). From 1991 until 1999, no such SED features were observed (Rogers et al. 2003).

39
40
41 The SED has been tracked extensively in the ground-based historical record. From this
42 record, we can mark the persistence of previous SED features, most notably from 1976 to
43 1989 and 1879 to ~1885 (Rogers 1995). On other dates, smaller features were observed
44 as cloud rifts extending from the SEZ to the SEB, but none lasted as long as a full SED
45 (Rogers 1995). The most recent SED has been monitored, both by appearance and by its
46 effect on the wind field, as a unique feature in accurate ground-based observations from

1 1999 to 2010 when it appears to have dissipated (Rogers and Mettig 2008). Online
2 Supplemental Figure S2 shows the track of the SED against the background chevron
3 features, from 2004 to 2010.
4

5 This most recent SED typically moved at ~ 90 m/s eastward, much slower than the
6 apparent wind jet speed, like previous SEDs (Maxworthy 1985, Sanchez-Lavega and
7 Rodrigo 1985, Beebe et al 1989, Rogers and Mettig 2008). When very active and well-
8 formed, anticyclonic rotation is seen in its core (Beebe et al. 1989, Rogers et al. 2005,
9 Garcia-Melendo et al. 2011). This is illustrated in Online Supplemental Movie M1
10 generated from a series of Cassini maps covering from October to early December 2000.
11 The SED rotation is apparent with dark material circuiting the core of the SED in about
12 10.5 days. The flow of the 7.5° S jet is clearly deflected south of the SED, with some of
13 the material entering the SED, and the rest passing by to the south, returning to its
14 original latitude along the bright ‘rift’ that marks the southeast edge of the SED. Small
15 patches of circulating material appear to be thrown off or form to the northwest of the
16 SED, sometimes interacting with NEZ plumes across the equator.
17

18 Note that at certain times the SED is quiescent, for example, in early 2002. During these
19 times, a blue-grey streak was observed in the SEZ alongside a white strip that marked its
20 location, enabling it to be continuously tracked as shown in Fig. S2 (Rogers and Mettig
21 2008). The blue-grey streak matches up well with the measured tracks from dates when
22 the SED was more conspicuous. Although its drift rate is not necessarily constant,
23 showing variations of a few m/s from year to year, as is the case for most large Jovian
24 features, it stands out in the velocity field as distinctly slower than surrounding clouds at
25 that latitude.
26

27 From ground-based data, the SED typically appears as a discontinuity or rift into the SEB
28 at visible wavelengths, though in its more quiescent state it is only delineated by a blue-
29 grey streak and white strip, as noted above and shown in the sketch in Fig. S2 (Rogers et
30 al. 2003, 2005). When active, it is also striking as a dark feature in methane gas-
31 absorption band imaging at 889 nm (Rogers et al. 2003, 2005). This is in contrast to the
32 NEZ plumes and adjacent cloud holes that are generally indistinct in 889-nm imaging.
33 The NEZ is covered by methane-bright haze, and occasionally a very active plume will
34 appear bright, while the nearby visibly dark clearings appear dark. In Hubble and Cassini
35 images, the small chevrons at 7° S typically behave the same way as the NEZ, with dark
36 visible cloud clearings corresponding to dark 889-nm features. In addition, most major
37 anticyclonic vortices, for example the GRS, are also bright at 889 nm and can be seen to
38 affect hazes up into the stratosphere at UV wavelengths. This is not the case for the SED.
39

40 Hubble (1998 and 2007) and Cassini (2000) images of the SED at various wavelengths
41 are shown in Figure 2. The absolute calibration of the Hubble 889-nm filter is somewhat
42 variable with time and location in the image (Karkoschka and Koekemoer 2002).
43 However, avoiding the worst, often saturated, areas of the filter, the relative brightness of
44 a cloud feature, can be compared with nearby clouds, to give a sense of relative
45 cloud/haze height and opacity. Given the brightness of the SED at visible wavelengths,
46 one would expect it to appear bright at 889-nm, similar to other high, thick, cloud

1 features. As Fig. 2 (middle panels) shows, the SED is dark at 889 nm, indicating a
2 clearing of the troposphere hazes above it. UV imaging, not shown, shows no indication
3 of any effect on the stratospheric hazes. Ground-based infrared imaging also indicate a
4 clearing of tropospheric haze or cloud (Terrile et al. 1979, Rogers et al. 2005).
5 Unfortunately, with limited wavelength, temporal, and emission angle coverage at high
6 spatial resolution, detailed radiative transfer analysis is not possible from this data for the
7 SED, making it difficult to quantify its vertical structure.

8
9 It is interesting to compare Hubble images from July 1998, before the SED formed, with
10 later dates (Fig. 2, left panels). No obvious plume feature is present in the cloud pattern
11 near 7° S in 1998, though a few dark streaks appear at latitudes between 4° S and 6° S,
12 and the standard chevrons are largely absent at these longitudes. However, anomalous
13 cloud/haze clearings are visible in the SEB in all filters, most obviously at 889 nm.
14 Occasionally darker cloud holes are present in this belt, for example as seen in Galileo
15 data in 1996 and sometimes in the turbulence west of the GRS, but are not usually as
16 distinct as the ones seen here (Vasavada et al. 1998, Simon-Miller et al. 1998). The SEB
17 showed strong convective activity on the western edge of this region at this time,
18 particularly obvious at 410 nm. This was part of an extensive convective outbreak
19 remote from the GRS which had started on or before March 1998, the first such outbreak
20 in five years (Rogers and Mettig 2001). Likewise, the long-lived SED observed by
21 Voyager appeared in 1976, about one year after a vigorous SEB revival (Sanchez-Lavega
22 and Rodrigo 1985, Rogers 1995).

23
24 The SED passes the GRS every 50 to 60 days or so, due to their differential east-west
25 motion. Its southern edge often interacts with convective structures within the SEB, most
26 notably the GRS ‘wake’ (convective disturbance) northwest of the GRS. After some
27 passages, the SED brightens noticeably, while in others it does not (Beebe et al. 1989,
28 Rogers 1995, Rogers et al. 2003, 2005). It has been proposed that this interaction with
29 the convective region might serve to sustain the SED (Smith et al. 1979, 1979b, Sanchez-
30 Lavega and Rodrigo 1985, Beebe et al. 1989). Although these effects are variable,
31 longer-term variations in the conspicuousness of the SED may also be consistent with its
32 being maintained by interaction with convective activity in the SEB.

33
34 In addition to the near-continuous activity west of the GRS, there have been mid-SEB
35 outbreaks of bright convective storms in 1998, 2003, 2005, 2007 (the SEB revival,
36 following a period of quiescence west of the GRS), and 2008. Resurgences of the SED in
37 2004 and 2006 followed the mid-SEB outbreaks in 2003 and 2005, as previously noted
38 (Rogers and Mettig 2008). The SED remained prominent in 2007 when the SEB activity
39 stopped, possibly because the subsequent SEB fading lasted only a few months before the
40 SEB revival began with its intense convective storms (see Rogers, J. H. “The South
41 Equatorial Jet and South Equatorial Disturbance, 2007: draft final report,” at
42 <http://www.britastro.org/jupiter/2007reports.htm>). The SED was strong again in 2008 as
43 the SEB revival was followed by extensive mid-SEB outbreaks, and it visibly interacted
44 with them on several occasions suggesting that these convective outbreaks could have
45 been supplying energy to maintain the SED, just as the convective region west of the
46 GRS has been proposed to do (see Rogers, J. H. “Jupiter in 2008: Full Interim report,” at

1 <http://www.britastro.org/jupiter/2008reports.htm>). However, it became quiescent after
2 passing the GRS in October 2008, and was never again a prominent feature. Further
3 details on this activity can be found in online interim reports of the British Astronomical
4 Association: <http://www.britastro.org/jupiter/2008reports.html>.

5
6 The SED was tracked in its quiescent form throughout 2009, and was probably recorded
7 as a weak feature in May 2010, but there was no trace of it thereafter. Thus, it
8 disappeared as the SEB “faded” and lost its usual dark coloration, replaced by white
9 clouds (Fletcher et al., 2011). The same had occurred in 1989, with that SED
10 disappearing as the SEB faded (Rogers 1995). As the SEB fading commences soon after
11 the complete cessation of SEB convective activity (Fletcher et al. 2011), this behavior is
12 also consistent with the hypothesis that interactions with SEB convective regions sustain
13 the SED. Therefore the birth, lifetime variations, and death of the SED were all broadly
14 consistent with such an effect, with a lag of ~ 6 to 12 months. This lag would consist
15 mainly of the time for changes in mid-SEB activity to spread to the northern part of the
16 belt; the actual response of the SED may be much faster, as it has often been seen to
17 intensify within about a week after passing the convective region west of the GRS.
18 However, the correlation is only qualitative, and cannot be defined precisely in time, so
19 any physical link remains hypothetical in the absence of a theory to explain it.

20 21 **2.2 Chevron morphology and periodicity**

22 In epochs without an SED structure, the pattern of small chevrons along the SEZ/SEB
23 interface can be seen at all longitudes, as shown in 1995 and 1996 in Fig. S1. These dark
24 features are typically separated by $\sim 2^\circ$ to 10° of longitude, and variation in distance
25 between features and their individual morphology is obvious in Fig. S1. Some form
26 distinct “v” shapes, while others are more extended, and still others appear temporarily as
27 only small dark spots. Nonetheless, these repetitive features appear somewhat periodic,
28 and global maps, particularly on dates without an SED, are ideal for searching for any
29 periodicity.

30
31 To search for periodicity indicative of potential wave structure, the global strip maps, as
32 seen in Fig. S1, were analyzed via Lomb-Scargle periodogram. For each date, the maps
33 were interpolated to the same scale (1800 x 50 pixels, spanning -2° to -12°) and the
34 brightness variation at -7.6° was analyzed, within the range of average chevron latitude in
35 these maps. Although the images were contrast enhanced, overly enhancing the contrast
36 or high pass filtering did not change the results, as the dark chevrons contrast well with
37 the intervening clouds. As shown in Figure 3, many significant periods ($< 0.1\%$ false-
38 alarm probability; power > 13.2) are found with 3° to 12° spacing, and we limit the
39 search to these short periods to avoid aliasing and confusion with very large structures.
40 Dates without an SED present are plotted in the top panel. For Feb. 1995, the date with
41 the most consistent chevron pattern, significant power is found at 3.8 and 4.4° , with few
42 significant peaks at longer separations, while data from Oct. 1995 and Oct. 1996 show
43 more peaks in the 6° to 12° range. These peaks are consistent with manual measurements
44 and reflect real differences in the chevron pattern; Feb. 1995 has tight chevron spacing
45 with ~ 100 features and an average spacing of 3.6° and a standard deviation of 1.9° . By
46 Oct. 1996 the chevron pattern is more chaotic, with some less distinct features and gaps

of 7° to 20° with no chevrons; these gaps show, to some extent, as peaks near 7° in the Fig. 3 periodogram for 1996. In this dataset, we manually measure ~ 75 distinct features with $4.5^\circ \pm 1.9^\circ$ average spacing if the largest gaps ($>10^\circ$) are not included, and $5^\circ \pm 3^\circ$ if they are included. This is consistent with the larger gaps, and less-distinct features, seen relative to Feb. 1995, and the lack of a single strong spectral power peak at short separations in the periodogram.

Dates with an SED, but normal, white, equatorial clouds are shown in the middle frame. On these dates, the detected periods are more tightly clustered around a 4° to 6° spacing. In 2000 the chevron pattern was very distinct, and about 80 features can be identified manually. The clear repeating chevron pattern should override the influence of the single SED on the periodogram at these small scales, but it is not clear why there would be a smaller spread in periods for these dates, particularly in 2000. From manual measurements, avoiding the SED, the average chevron spacing is $4.1^\circ \pm 1.8^\circ$, slightly lower than that found in the periodogram. Thus, it would be difficult to establish a correlation between the presence of the SED and the chevron spacing from these dates, as there appears to be little difference.

Finally, dates with an SED, but an anomalously “clear” EZ are plotted in the bottom panel of Fig. 3; in these months the SEZ was darkened with an orange or grey-brown shading, and the chevrons were less visible or absent entirely. For both June 1979 and Mar. 2007, no peaks are seen below about 7° spacing. In these cases, the shortest period power signals disappear, due to the lack of closely spaced cloud tracers, though power is seen from 11° to 15° spacing. Note that the SED core, measured by internal motion, spans about 8° , while the extended wing-shaped plume can extend for 30° to 50° , though the exact eastern edge can be difficult to discern (*c.f.*, Maxworthy 1985, Sanchez-Lavega and Rodrigo 1985, Rogers 1995, Rogers and Mettig 2008, Garcia-Melendo et al. 2011). On these dates, particularly in March 2007, an extended pattern of large plumes was visible east of the SED, with features $\sim 15^\circ$ to 20° in extent. From these admittedly limited data, the chevron pattern appears to be correlated more with equatorial clouds than with the presence or absence of the SED, and may be entirely independent of both.

3. Chevron Motions and Latitude

Another interesting aspect of the chevrons is their velocity and latitude variation. As Table 1 shows, dates with full longitude coverage from spacecraft data are rare, but many other data sets exist with limited longitude coverage from spacecraft, or more extensive coverage from ground-based observers. Any time-separated images of the same longitudes can be used to determine wind velocities, as long as cloud features can be resolved. In the highest spatial resolution Voyager and Galileo imaging data, time separations of less than an hour can be used to determine the smallest of motions with low uncertainty. As resolution degrades, contrast decreases on smaller features, and it becomes necessary to track over longer time periods to decrease the uncertainty in cloud motion measurements, as long as the feature has not changed significantly and can be uniquely identified. In practice, both high-resolution, short-time-separation, and lower-resolution, longer-time-separation measurements give essentially the same results for the jet peak, dominated by the motion of the chevrons (Rogers and Mettig 2008).

The spacecraft images were navigated using common least squares ellipsoid limb fitting techniques. The amateur ground-based data, were also navigated using limb fitting, and refined by moon positions, and the known latitudes of features such as the GRS, allowing positions to be measured to better 0.4° . Feature locations were recorded using the JUPOS project software (see <http://jupos.org> for a complete description of the process and its history, and additional details below). The compiled database of positions was then converted into accurate drift rates.

3.1 Chevron Velocity

Using the Hubble data shown in Table 1, individual chevrons were first tracked using manual measurements. Although the SED was present in 2000, 2007 and 2008, the longitudes available in the Hubble wind pair images did not include the SED. In each image pair, the chevron velocity was measured at the sharp peak of the feature when at all possible, using the leading, eastward edge, of the dark feature regardless of latitude, unless that edge was too diffuse to cleanly identify. Each point has a maximum uncertainty of ~ 8 -15 m/s, based solely on time separation, spatial resolution and the location on the visible disk (i.e., points closer to the limb show more foreshortening and larger uncertainty). As shown in Figure 4, top, the velocity of the individual chevrons is variable, even in close proximity to each other, with values ranging from ~ 135 m/s to 165 m/s. On dates when the SED was absent, 1996 and 1998, maximum velocity values are more consistently near 160 to 165 m/s. For other dates, when the SED was present but far from the measured longitudes, maximum velocities typically did not exceed 155 m/s. However, the sparseness of the data makes it difficult to draw many conclusions.

Two global wind data sets are also available, from the Voyager and Cassini missions. Both Voyager 2 and Cassini image map pairs were analyzed with autocorrelation techniques, rather than manual tracking, following the method of Choi and Showman (2011). This automated method first uses a large correlation box of 2° square, and then refines results with a smaller 1° square box, yielding many more points than in the manual measurements, though not detecting the smallest of features. The uncertainties are estimated at ~ 5 - 10 m/s from correlation box size and image resolution. Note that the Voyager 2 maps had so few distinct clouds (using the blue/violet movie rotations) at this latitude that the correlation did not provide useful results, while the high contrast in the Cassini data gave much cleaner results, as shown in Figure 5 at 7.5° S (6.5° centric latitude).

In the Cassini correlation shown in Fig. 5, top, the average feature velocity is ~ 135 to 140 m/s, with a spread of about ± 10 m/s confirming Porco et al. (2003) and Li et al. (2006). The apparent discontinuity between velocities at 0° and 360° in these plots is due to motion of features over the time elapsed in a rotation, and the ability of the correlation to match features near image boundaries. The white clouds between the dark chevrons appear to move more slowly than the chevrons themselves, though in some cases this is due to lack of distinct trackable features. The bottom panels of Fig. 5 display a portion of the Cassini maps with east-west velocities overlain and scaled from 30 m/s (black/purple) to 160 m/s (red). These graphically illustrate the large-scale speed variation caused by

1 the SED, confirming the results of Garcia-Melendo et al. (2011), but with higher
2 resolution to show the dynamics of the chevron pattern.

3
4 Thus, the features at this latitude show true dispersion in their velocity, both in
5 contiguous cloud features and over greater longitude spans. Chevron velocity is nearly
6 constant west of the SED, and then accelerating as they approach the feature from 280° to
7 230° W and are drawn in to the local flow. The western edge of the SED is present at
8 $\sim 220^\circ$ W longitude and appears as a sharp discontinuity, drifting at ~ 80 to 90 m/s,
9 consistent with prior measurements of Voyager and ground-based data (Smith et al.
10 1979b, Maxworthy 1985, Sanchez-Lavega and Rodrigo 1985, Rogers and Mettig 2008).
11 The SED affects cloud velocities to the east for some distance before cloud tracers slowly
12 return to the peak speed, reinforcing previous results from ground-based feature tracking
13 from 1999 to 2006 (Rogers and Mettig 2008).

14
15 Ground-based data also provide long-term coverage of chevron motions with and without
16 an SED present. Typically, the ground-based images used for measurement are from
17 numerous amateur observers around the world, whose names are posted on the BAA web
18 site (<http://www.britastro.org/jupiter/reports.htm>). Measurements of a cloud feature's
19 latitude and longitude are made on-screen using the WinJUPOS program (created by G.
20 Hahn), which is fully described and available at (<http://jupos.org>) and can be recorded
21 into a database. The database contained 53,176 measurements for the 2008 apparition
22 and 105,118 for the 2010 apparition. Drift rates were derived by least-squares fit, and
23 measurements have a typical standard deviation of $\sim 0.4^\circ$. Standard error of latitude is
24 $< 0.2^\circ$ because many points (at least 5, usually many more) are averaged for each spot.
25 Uncertainty in drift rate is conservatively estimated as $2 \times 0.4^\circ$ divided by track duration
26 in days; typical uncertainty for an 8-day track is $0.10^\circ/\text{day}$, or 1.4 m/s.

27
28 As seen in the Cassini data, ground-based records show that the presence of the SED
29 alters the flow to the east, and sometimes around the entire planet, resulting in lower
30 measured average feature speeds (Rogers and Mettig 2008). Similar results are found
31 from 2008 ground-based data, with higher spatial and temporal resolution than in
32 previous years due to increased amateur use of webcam imaging and processing software,
33 as shown in Figure 6. The SED was conspicuous in 2008, sometimes displaying its
34 classic plume-shaped morphology, and sometimes more variable (see Rogers, J. H.
35 "Jupiter in 2008: Full Interim report," <http://www.britastro.org/jupiter/2008reports.htm>).

36
37 The chevrons were conspicuous in 2008, especially in a regular array east of the SED
38 with spacing 8° and increasing eastward to 9° . The chart of longitude versus time shown
39 in Fig. 6, confirms the pattern previously reported: the chevrons move more slowly east
40 of the SED, and accelerate with increasing distance Online Figures S3 and S4. Over the
41 year, many individual chevrons were tracked as they accelerated in this flow. Final
42 averages of distances, speeds and latitudes are given in Table 2. These results show a
43 gradient of speed covering $\sim 160^\circ$ of longitude east of the SED. Around the remaining
44 longitudes, most chevrons move with the peak speed of ~ 140 m/s, though there are also
45 a few slower moving ones, as well.

1 In contrast, Figure 7 shows the results from 2010, after the SED disappeared. From June
2 onwards, the alternative regime had taken over, seen in previous years when the SED was
3 less active (Rogers and Mettig 2008), but now recorded with improved precision and
4 detail. There were long-lived bands of disturbance (revealed by a high density of
5 measurable dark features in Fig. 7), moving with the maximum speed (158 ± 2 m/s);
6 some individual chevrons moved at this speed, but many other chevrons moved more
7 slowly (~ 132 - 144 m/s), see Table 3. The disturbed sectors of the 7.5° S jet were often
8 conspicuous in high-resolution images, such as the top strip map in Fig. S1.

9
10 Within the 2010 observations, it was evident that slower chevrons tended to appear,
11 whether single or multiple, within the fast-moving larger clusters (Fig. 7). We examined
12 7 examples in detail, those where the initial JUPOS chart suggested that individual spots
13 had decelerated within a cluster, to test whether the slow spots had formed anew or by
14 deceleration of pre-existing fast spots. In these case studies we plotted the JUPOS data at
15 higher resolution and also compiled the images so as to follow individual spots within
16 these complex and rapidly-changing clusters. One example contained seven slow-moving
17 spots; the others had one or two (*e.g.*, Fig. S5), although some neighboring spots with less
18 well characterized tracks may also have decelerated.

19
20 High-resolution images showed that both fast and slow chevrons had similar
21 morphologies. The slow chevrons tended to occur within dense clusters of chevrons that
22 had sometimes formed anew, and some came from existing faster chevrons that
23 decelerated over a few days, or were generated by splitting of faster features, as seen in
24 online Figure S5. These slower spots were shorter-lived: mean duration of track was 8.6
25 days for slow spots, 17.6 days for fast spots (significant at $P < 0.01$ by Student's *t*-test;
26 Table 3). They also appeared to be slightly further north.

27 28 **3.2 Chevron Latitude**

29 The question naturally arises whether the difference in chevron speed can be attributed to
30 a change in latitude, as features move in and out of the peak of the zonal wind jet. To test
31 if latitude is affecting the chevron velocity, latitude from the spacecraft images is plotted
32 against velocity in the bottom panel of Fig. 4, with representative error bars shown on the
33 2008 Hubble data. The solid line indicates the Cassini zonal wind profile, found via
34 correlation, from Porco et al. (2003), and over these latitudes there is little variation in
35 velocity. As can be seen from the manual measurements, there is no strong correlation
36 between latitude and velocity, and all the manual measurements exceed the correlated
37 zonal wind velocity. Chevron latitudes were also measured manually on several of the
38 global maps and give an average latitude of 7.5° S $\pm 0.3^\circ$ for Feb. 1995, 7.4° S $\pm 0.2^\circ$
39 for Oct. 1996 (both Hubble), and 7.5° S $\pm 0.4^\circ$ for December 2000 (Cassini).

40
41 The mean latitude from 2008 ground-based data was 7.2° S $\pm 0.3^\circ$, with no correlation
42 of speed with latitude. Some of the slow-moving features closest to the SED had slightly
43 higher latitudes, probably because the wind jet was deflected by the SED itself. Note that
44 the ground-based values refer to the centroid of the chevron, which likely explains the
45 slight latitude difference from the spacecraft measurements of the eastern peak. Likewise
46 from the ground-based data in 2010, it can be seen that the slow features had almost the

1 same latitudes as the fast features (Table 3), within the range of the wind jet peak,
2 However, in the 7 examples studied in detail, slow chevrons which decelerated or split
3 off from faster chevrons were always further north than the faster ones, by an average of
4 $0.36^\circ \pm 0.15^\circ$. This was likely not because the chevron itself shifted north, but typically
5 because its northern limb became darker or detached altogether from the dynamical
6 pattern in the jet. Again, the slight latitude shift is not nearly enough to account for the
7 slow speeds based on the cloud top zonal wind profile alone, which would only give a
8 few m/s variation, as shown in Fig. 4, bottom.

10 **4. Chevron Oscillations**

11 To further understand the chevrons' motions, a detailed series of movies was constructed
12 covering the Cassini flyby approach (Oct. 1, 2000 to Dec. 9, 2000) and registered to be
13 co-moving at the approximate chevron speed, 140 m/s (see Supplementary Online
14 Movies M2-M5, each spanning $\sim 90^\circ$ of longitude). Flow around the SED has already
15 been described, with chevrons approaching the SED rapidly from the west, drawn south
16 and destroyed (one every 2 days on average). As the flow emerges east of the SED, new
17 white clouds appear, along with dark features, starting as "pulses" southeast of the SED
18 as it interacts with the SEB. Coherent chevrons form east of that interaction once past the
19 initial turbulent region that extends for tens of degrees.

21 These chevrons can be seen to vary in many aspects; a chevron may alternately lead and
22 lag the movie frame velocity, the chevrons sometimes split, dissipate entirely, or re-form,
23 and some of the white clouds and delineating chevrons show cyclonic circulation.
24 Occasionally a fast dark spot will appear to race across the chevron pattern at high
25 velocity (see annotations in the Online Movies). In addition, the northern extension of
26 the chevrons and clouds appear to interact with the southern extensions of, and gyres
27 formed beneath, the NEZ plumes.

29 However, the most striking discovery in the movies is that the chevrons oscillate in
30 latitude, with a well-defined period of 6.7 ± 0.7 days (from manually tracking 12
31 chevrons with a total of 58 oscillation cycles). This oscillation is particularly obvious in
32 movies, and sample features from movie frames are shown in Figure 8 with lines marking
33 the maximum and minimum points of the oscillations. The oscillating chevrons are the
34 predominant features along the wind jet, excluding the region east of the SED, with a
35 mean velocity of 146.6 ± 3.5 m/s. The chevron latitude varies from a crest at 6.6° S to a
36 trough at 8.5° S in the highest amplitude cases.

38 Although the oscillating chevrons are often long-lived, their appearance changes
39 throughout the ~ 7 -day cycle, and in some cases the chevron is only well defined at the
40 trough of the cycle. During the crest of the oscillation, the feature can appear as anything
41 from a fully formed chevron to merely a small streak, and they often appear to "leap"
42 before descending. At the trough, when it contacts the SEB edge and may interact with
43 slower-moving short-lived features, it becomes enveloped in expanding, slower-moving
44 dark material that forms the well-defined N and S limbs of the chevron, as seen in the
45 annotated Supplemental Movies. In this phase it often shows a distinct cyclonic
46 circulation from the incoming streak (N limb) to the expanding S limb, whose tip shows a

1 typical speed of ~ 116 m/s at 8.4° S consistent with the zonal wind profile (*e.g.*, Porco et
2 al 2003).

3
4 The chevron also has a variable N limb; sometimes it accompanies or trails after the fast
5 dark peak, other times it emerges in anticyclonic rotation as the chevron begins its
6 upswing. There is also much variability in appearance due to small-scale turbulence and
7 ephemeral slower-moving features; hence, the oscillations cannot be reliably identified
8 except from the movies. In fact, although single global maps show variation in chevron
9 latitude, as discussed in Section 3.2, any searches for periodicity in latitude, and hence a
10 standing wave, yield null results. This is almost certainly because feature morphology is
11 variable and a chevron tip does not always correspond to the exact crest or peak of the
12 wave at that instant in time; a single view or latitude measurement can not clearly
13 delineate the wave.

14
15 The origin of the chevrons and of their oscillations, east of the SED, can also be seen in
16 detail in the movies. Proceeding east from the SED, the 7.5° S cloud structure is initially
17 complex with large chaotic dark features – sometimes forming from little dark blobs that
18 emerge from the SED, sometimes forming at the mouth of the SED's bright southern rift
19 – and engaging in complex interactions for tens of degrees downstream, including
20 anticyclonic swirls in the SEZ. Faster spots are intermingled with these slow features,
21 but are still slower than the fastest spots further east. Regular arrays of chevrons are
22 sometimes seen some tens of degrees east of the SED (typical speeds of ~ 132 m/s), more
23 coherent than further east and not yet oscillating. Oscillations begin ~ 50 to 60° east of
24 the SED, and the initial oscillations often have high amplitude.

25
26 The mean eastward speed of the oscillating chevrons, 146.6 ± 3.5 m/s, is faster than the
27 mean speed found in some previous studies of 2000 data by feature tracking (142 m/s: Li
28 et al. 2004, Rogers and Mettig 2008) or correlation (137 m/s: Porco et al. 2003, this
29 study), but consistent with the manual measurements from the Sep. 2000 Hubble data in
30 Fig. 4. The difference may be because the oscillating spots are most conspicuous as
31 chevrons at the trough of the cycle, when they develop slower-moving dark extensions to
32 N and S, so the well-formed chevron is actually a transient feature with an apparent speed
33 slightly less than that of the persistent faster-moving spot. Chevrons with this aspect may
34 have dominated the previous determinations of speed and latitude. This behavior is also
35 visible in Fig. 5, bottom, where the fastest speeds (red) tend to coincide with the northern
36 limbs of chevrons, presumably where oscillating streaks are separate from slower-moving
37 material.

38
39 As these dark features on the jet are oscillating, one might expect that they trace a
40 coherent wave on the jet. Manually tracking the troughs of all oscillations on a subset of
41 the Cassini movie maps reveals that the motions trace waves with a speed of 101 ± 3
42 m/s in System III and a wavelength of $\sim 20^\circ$, as shown in Fig. 8. This is almost identical
43 to the mean speed of the array of plumes seen in the NEZ, which moves at 100-105 m/s,
44 slower than the true wind jet speed (Li et al. 2006, Garcia-Melendo et al. 2011). In
45 addition, some of the wave trough tracks coincide with the tracks of the large NEZ
46 projections. This confirms the impression from the movies that the chevrons tend to

swing southward around the large anticyclonic circulations south of the large NEZ plumes, especially in the first oscillations east of the SED.

5. Discussion

5.1 Large-Scale Planetary Waves

There has been much discussion of possible waves on jovian jets, particularly Rossby waves, to explain either the visible features such as the NEZ plumes (Allison 1990), or the maintenance of the jets themselves (Schneider and Liu 2009, Wood and McIntyre 2010). The periodic spacing of the 7° N dark projections ('hot spots') and plumes naturally suggested that they represent a planetary-scale wave phenomenon. Allison (1990) proposed that they are Rossby waves, confined in latitude by the planetary vorticity gradient, with a vertical structure or equivalent depth corresponding to the normal modes of an assumed statically stable layer deep below the cloud tops.

This model has been reinforced by subsequent theoretical studies (Dowling 1995, Ortiz et al. 1998, Showman and Dowling 2000, Friedson 2005, Garcia-Melendo et al. 2011). The dark formation represents the region of downwelling at the trough of the wave, within which most of the clouds evaporate. The model is supported by the correlation of wavenumber with phase speed, predicted for Rossby waves and observed for the NEZ plumes (Ortiz et al. 1998, Arregi et al. 2006, Garcia-Melendo et al. 2011). The model is also consistent with partial anticyclonic circulation observed south of some large NEZ plumes seen in Voyager and Galileo data (Beebe et al. 1989, Vasavada et al. 1998), and confirmed in the Cassini data (Garcia-Melendo et al., 2011, Asay-Davis et al. 2011). This anticyclonic gyre is reproduced in one version of the Rossby wave model (Showman and Dowling 2000) but not others.

The SED may be explained as a similar feature with wavenumber 1, as proposed by Maxworthy (1985) and Allison (1990). Its slow phase speed and its well-formed anticyclonic rotation are consistent with the trapped Rossby wave model. The wave-like pattern in chevron latitude oscillations, with an apparent speed of 100 m/s, further reinforces the idea of a large-scale wave on this jet. The expansion of a typical chevron at the trough of the wave leads it to sometimes resemble the 7° N formations and the SED, in terms of the dark bluish patch and the flow pattern around it, including partial anticyclonic flow on its equatorward side. This characteristic structure is visible transiently, for a few days, when a dark spot running along the jet passes through the trough of its cycle. The long-term persistence of this wave is unclear, however, as without adequate temporal monitoring, the wave can only be confirmed in the Cassini 2000 data.

The SED is moving eastward with a speed of 75 to 90 m/s, relative to System III longitude, at 7.5° S. From the dispersion relations in Allison (1990) or Garcia-Melendo (2011), this would imply an $n=1$ Rossby wave with equivalent depth between 1 and 10 km depending on mode and true wind jet velocity at the proper depth. This is not much different than the wave modes found for the NEZ plumes, with slightly higher velocity but also higher wavenumber. If we assume that the 7-day chevron latitude oscillations also represent a Rossby wave, they can be analyzed likewise. For a wave with $n=18$,

(higher n than for the NEZ plumes), the equivalent depth is between ~ 1 to 10 km by these linearized relationships (*c.f.*, Garcia-Melendo et al. (2011) Fig. 10 and Allison (1990) Fig. 5).

However, the numbers of NEZ plumes have proven to be variable: in 2000, there were seven large NEZ features, spaced ~ 35 to 70° apart. At this time the SEZ wave, with a wavelength of 20° , would have two to three cycles between successive NEZ plumes. More typically, the NEZ has 11 to 15 plumes (25° to 35° spacing), as seen during the Voyager and New Horizons flybys (Smith et al. 1979 a, b, Sanchez-Lavega and Rodrigo 1985, Rogers 1995). In addition, the SED and chevron wave crests seem to interact with NEZ plumes; they often spatially align, but there is also complex motion around the equatorial gyres seen in the Cassini movies. The presence of the NEZ plumes, and the passage of the SEZ jet past the associated anticyclonic gyres could initiate or reinforce the oscillations and constrain the size of the SED and any wave. During the New Horizons flyby in 2007, the SED was duplicated and additional white areas gave a transient impression of a wave-train with $\sim 30^\circ$ wavelength along the SEZ, as seen in Fig. S1 and S2. Thus, the $\sim 20^\circ$ wavelength in chevron latitude crests seen in 2000 may be variable, like that in the NEZ, but further movie data from other epochs, with and without an SED, would be required to better constrain large-scale wave persistence and wavelength.

5.2 Nature of the Chevrons

In the movies, the chevrons seem to be material tracers of the flow field, in that they trace the large-scale wave pattern, but move at higher velocity. As suggested by Garcia-Melendo et al. (2011) the variable chevron speeds could be modeled as disturbances in the cloud deck which trace the true wind speeds at variable depths, assuming that the 7.5° S jet, like the 7° N jet, increases in speed with depth below the cloud tops. At many longitudes in Fig. 5, one can see a velocity difference of ~ 20 m/s between the faster chevrons (especially their northern limbs) and the slower bright features between them. As shown in Simon-Miller et al. (2006, 2007), this is consistent with the bright features being clouds at higher altitude: the difference in cloud level would be ~ 60 -100 mbar, near the top of the visible cloud deck at ~ 500 mbar, using the Cassini CIRS temperature retrievals and the thermal wind equation at this latitude. This is a plausible range for cloud height variations at this latitude, as shown in Simon-Miller et al. (2001). Indeed, the chevrons themselves appear to be holes in the clouds, but there is substantial difficulty in determining the absolute vertical cloud structure, and any variations, of these very small features; attempts to do so have failed to successfully converge

Feature tracking, whether manually or by correlation, preferentially picks cloud features or chevrons, and there is no way to know if any of the features are tracers of the actual wind jet velocity. It is unclear if the faster or slower features are the ones disconnected from the wind jet, as there is evidence for either case. For example, some of the slower chevrons have shorter lifetimes than fast features, as seen in the ground-based data from 2010 in Table 3 and in the Supplemental Online Movies, and perhaps those are not rooted as deeply in the base wind jet. On the other hand, the ground-based data in 2008 show slightly increased chevron spacing as velocity increases east of the SED, with slower

1 features in denser clusters, possibly a correlation between velocity and spacing.
2 Similarly, the sparse velocities measured for 1995 were slightly slower than those for
3 1996, with more chevrons present in 1995. In general, the data are too sparse to draw any
4 conclusions about a correlation between chevron velocity and lifetime or spacing.

5
6 The shape of the features is also not diagnostic, as wind shear on clouds along the sharply
7 defined jet should preferentially result in a chevron shape, though interestingly, such
8 features not seen at 7° N, nor on the high speed wind jet at 23.5° N. If there is symmetry
9 with the jet at 7° N, wind jet velocities may reach 170 m/s at 5 bars, but decrease with
10 higher altitude to the cloud tops. This deep jet velocity could be masked in the presence
11 of the SED, at least at the cloud top level, as has been inferred for the 23.5° N jet during
12 large-scale climatic cycles (Sanchez-Lavega et al. 2008). Alternately, the true cloud-
13 level jet velocity may be 140 m/s, with faster chevrons indicative of an eastward
14 propagating wave with small dispersion.

15
16 If we assume that the repetitive nature of the chevrons is indicative of a wave, the
17 linearized Rossby wave approximation used in Allison (1990) and Garcia-Melendo et al.
18 (2011), show that wavenumbers above ~ 70 all approach the speed of the wind jet, so
19 there is no way to distinguish between equivalent depth and wave mode at these high
20 wavenumbers. In addition, these Rossby modes would be susceptible to critical layer
21 absorption as their low phase speeds are smaller than the integrated vertical/horizontal
22 shear. However, Allison (1990) also proposed gravity-inertia, Kelvin and Yanai waves
23 modes for the Jovian atmosphere (see his Figure 5 and Table 1) and as possible
24 explanations for the chevron features. With chevron velocities 0 to 25 m/s different than
25 the zonal flow, an eastward gravity-inertia wave with these phase speeds would require
26 very small equivalent depths of < 40 m. It should be noted that these linearized wave
27 dispersion models do not take into account wind shear, and many other aspects of the true
28 atmosphere, and may not represent a realistic dynamical picture. However, in a separate
29 analysis, Allison and Atkinson (2001) showed that residuals in the Galileo Probe Doppler
30 signal were consistent with a vertically propagating gravity-inertia wave between 1.5 and
31 4 bars, with small equivalent depth and low relative phase speed.

32 33 **5.3 Equatorial Asymmetry and Stability**

34 Despite an apparently symmetric wind jet structure, an important question remains as to
35 why there is such a large difference in the visible cloud structure between the two
36 regions. At 7.5° S the dominant cloud feature is the chevrons, with the occasional long-
37 lived SED, while there is usually a regular array of multiple NEZ plumes at 7° N. During
38 the Voyager era, this difference was attributed to the interactions of SEB convective
39 activity with the 7.5° S jet (Mitchell et al. 1979). However, similar convective activity
40 and interaction occurs at the NEB/NEZ interface as well, and the NEZ plume pattern is
41 well established (Beebe et al. 1989, Rogers 1995). Thus, the simplest reason why one
42 dynamic pattern is preferred over another in the two regions may be the presence (or lack
43 of) a long-lived large vortex like the GRS that subtly disturbs the flow or stability from
44 the poleward side, as suggested by Allison (1990). While dark vortices and ‘barges’ are
45 seen in the NEB from time to time, none are as large or persistent as the GRS, nor do
46 they extend as far in latitude (Beebe et al. 1989, Rogers 1995).

1
2 Note that in the historical record from ~1870 to 1910, many reports showed the SEZ
3 filled with numerous dark projections and fewer plumes in the NEZ (Rogers 1995). At
4 the same time, although cloud structures suggesting the edge of a vortex were seen
5 repeatedly in the early to mid-1800s, the GRS was not recognized in its present form until
6 the 1870s when it was visibly red and distinct, but extended $\sim 30^\circ$ in longitude, much
7 larger than today, suggesting it is not a permanent feature (Rogers 1995). During the
8 early era of multiple SEZ plumes, a number of micrometer measurements, albeit of
9 unknown accuracy, place the GRS further south, at 23.5° S to 25° S latitude (Peek 1958),
10 than is observed today, though there is no obvious correlation between SED appearances
11 and GRS latitude shifts, Fig. 9.

12
13 However, many studies have speculated that the mere presence of a GRS affects the
14 stability of the region and could explain the disparity in dominant wavelength or type and
15 cloud appearance between 7° N and 7.5° S (*c.f.*, Beebe et al. 1989, Allison 1990).
16 Comparing the Voyager zonal wind profiles, Ingersoll et al. (1981) found that the
17 westward wind jets were subject to barotropic instability (large wind shear drives eddy
18 mixing which then lowers the shear), while eastward (prograde) wind jets were very
19 stable. Baroclinic instabilities are possible, however, and horizontal disturbances and
20 gradients can cause vertical wind shears and vice versa. Quasi-periodic outbursts of
21 strong convection in the SEB, and around the GRS could cause a change in stratification
22 and overturning. For example, a moist convective event that leads to large latent heat
23 release, such as the activity outbreaks seen in 1998 and 1999 before the SED formation,
24 can form instability that slowly radiatively relaxes toward the initial state. As the
25 observed outbursts are variable in strength, size and timing, there is no reason to expect
26 the symmetric wind jets near 7° N and 7.5° S to be in phase. The NEB also has such
27 activity, though perhaps less energetic than the GRS wake and SEB interactions.

28
29 In addition, while simulating Jupiter's equatorial superrotation, Schneider and Liu (2009)
30 also found that prograde wind jets are more susceptible to baroclinic instabilities, and that
31 eddies are responsible for momentum transport and generating off-equatorial wind jets.
32 This is not surprising, though that particular model used artificial conditions, such as a
33 boundary at 3 bars, and stability criteria that may not be realistic for Jupiter.
34 Nonetheless, it confirms that equatorial superrotation is driven through momentum
35 transport from poleward propagating Rossby waves created by convective heating in the
36 equatorial region (Schneider and Liu 2009, Wood and McIntyre 2010). Near the equator,
37 these Rossby waves had a characteristic wavenumber of ~ 10 and a westward phase
38 velocity of 50 to 100 m/s relative to the zonal flow (Schneider and Liu 2009). This is
39 consistent with the 7° N plumes, which have speeds roughly 60 m/s lower than the wind
40 jet speed, and with the hypothesis of a Rossby wave at 7.5° S.

41
42 With meridionally propagating waves, the very different structure along the two jets
43 could also be caused by destructive wave interference. An example of this is an El Niño
44 cycle on the Earth, where equatorial Kelvin waves alter the ocean temperature gradients,
45 which in turn alter the winds driving the waves in a positive feedback loop (*c.f.*, Philander
46 1990). These Kelvin waves spawn Rossby waves that eventually reflect off land and

destructively interfere breaking the cycle. This process is slow and can take many months, leading to extended periods of El Niño conditions.

On Jupiter, the frequent passages of the GRS and its large turbulent wake may serve as a boundary that reflects large-scale waves back towards the equator and finally breaks the SED cycle. In the northern hemisphere there is no such boundary or deflection mechanism, unless a large vortex or persistent barge should form, and the wave activity will continue until meridional propagation ceases (Schneider and Liu 2009). On the Earth, the wave deflection and interference process is slow and only partially predictable, so it would not be surprising for a similar process to take many years on Jupiter, particularly as the location and size of the GRS and its wake are variable. A combination of this type of wave interference, and quasi-periodic changes in stability and convection, may both contribute to the observed cloud pattern. Future studies with General Circulation Models (GCMs), constrained by long period movies, are needed to fully understand the effects of each mechanism in forcing the region's structure.

6. Conclusions

Consistent with prior studies, a thorough analysis of chevron motions shows velocity variation in the presumed tracers of the 7.5° S wind jet over time and longitude. When the SED is not present, most chevrons have high velocity, indicating that interaction with the SED suppresses the velocities of the features. The most detailed analysis, available from Cassini image movies and long time coverage ground-based data, shows that individual chevrons can have a wide dispersion in velocity, and accelerate as they move further from the SED. The chevrons themselves change on short time periods and often a fast feature will spawn other, slower, features, as well. Their apparent phase velocity and persistent and repetitive pattern is consistent with an eastward gravity-inertia wave.

The chevron latitudes are variable during all epochs, but with the detailed motions discernable in the Cassini movies, oscillations in latitude are visible. This remarkable oscillation in latitude has a period of 7 days, following a coherent wave pattern with phase speed 101 ± 3 m/s and wavelength $\sim 20^\circ$. The transient appearance of the chevrons at the trough of each cycle has dynamical similarities to the NEZ plumes and the SED, supporting a Rossby wave model for all of these planetary-scale features. The wave may be further reinforced by the anticyclonic gyres associated with the NEZ plumes, as indicated in the interactions seen in the Cassini movies.

The asymmetry in wave or cloud structure along the SEZ and NEZ wind jets is likely due to the presence of the GRS. Variable convective activity caused by GRS interactions may temporarily change the static stability of the region. In addition, a cycle of wave generation and interference may also be present; the SED and any induced Rossby waves may be visible manifestations of that cycle that are eventually disrupted by the GRS and strong convection in the SEB. To fully constrain the wave modes present and the effects of the GRS, further observational data and modeling are needed. Vertical cloud and wind structure would best be constrained by atmospheric probes, but high resolution data sets with proper emission angle coverage, refined methane absorption coefficients, and radiative transfer modeling methods may also set limits. In addition, computationally

1 intensive GCMs are required to reproduce both wind jets and propagating waves, with the
2 added effects of vortices cause on convection, dynamics and stratification, and realistic
3 boundary conditions.

4
5 Finally, we conclude that time-lapsed movies covering many Jupiter months are critical
6 for understanding vortex interactions and dynamical flow. The limitations of snapshot
7 data become apparent when trying to draw conclusions on the motions in the 7.5° S jet
8 from ground-based or Hubble data alone. In this case, the latitude oscillations and larger
9 wave structure were only evident after observing the motions in the movies. We expect
10 similar unexpected findings to emerge in the analysis of other regions, as well. This
11 underscores the importance of regular dynamical monitoring of planetary atmospheres by
12 future missions, in particular over long timescales of many months or years.

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32
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Table 1. Data sets analyzed

Source	Date	Purpose
Voyager 2	June 1979	Global map, chevron periodicity
Hubble	Feb. 1995	Global map, chevron periodicity, latitude
Hubble	Oct. 1995	Global map, chevron periodicity, velocity
Hubble	Oct. 1996	Global map, chevron periodicity, velocity, latitude
Hubble	July 1998	Chevron velocity
Hubble	August 1999	SED morphology
Hubble	Sep. 2000	Chevron velocity
Cassini	Oct.-Dec. 2000	Global map, chevron periodicities and latitude, chevron and SED velocities, movies, SED morphology
Hubble	Feb.-Mar. 2007	Global map, chevron periodicity, velocity, SED morphology
Hubble	May 2008	Global map, chevron periodicity, velocity, SED morphology
Ground-based	2008, 2010	Chevron and SED velocities, morphology

Table 2. Spot/chevron speeds as measured in 2008 ground-based data*

Longitude (° east of SED)	U (m/s)	Graphic Lat. +/- Std. Dev.	Number
0-45	120.0 +/- 1.3	-7.5 +/- 0.3	12
45-110	126.0 +/- 3.1	-7.2 +/- 0.2	26
110-160	135.2 +/- 2.8	-7.4 +/- 0.2	5
220-320	139.9 +/- 4.0	-7.2 +/- 0.3	6

* omitting five spots anomalously slow for their longitudes

Table 3. Spot/chevron speeds as measured in 2010 ground-based data

	U (m/s)	Graphic Lat. +/- Std. Dev.	Number	Duration (days)
<i>All dates</i>				
Fast spots	156.4 +/- 3.6	-7.4 +/- 0.2	26	17.6 +/- 13.5
Slow spots	139.6 +/- 5.0	-7.4 +/- 0.2	34	8.6 +/- 4.6
<i>June-July only:</i>				
Fast spots	158.5 +/- 3.4	-7.4 +/- 0.2	7	17.4 +/- 8.7
Slow spots	138.1 +/- 4.1	-7.1 +/- 0.3	6	5.3 +/- 3.3
<i>Aug-Nov. only:</i>				
Fast spots	155.6 +/- 3.5	-7.4 +/- 0.1	19	18.1 +/- 15.0
Slow spots	139.2 +/- 7.5	-7.4 +/- 0.2	24	8.0 +/- 2.7

Figure Captions

Figure 1. Annotated context map of Jupiter. This Cassini map, reproduced and re-centered from PIA07782, was acquired Dec. 11 and 12, 2000. Labels have been added to denote the SED and a group of well-defined chevrons. Credit: NASA/JPL/Space Science Institute

Figure 2. Cloud structure of the SED as seen in visible and near-IR filtered images. Maps generated from Hubble and Cassini (2000) images are shown for July 16, 1998 (pre-SED formation), Aug. 11, 1999, Dec. 11, 2000, Feb. 26, 2007 and Mar. 26, 2007. Each is centered on 7° S latitude and spans $\pm 30^\circ$ of longitude and $\pm 20^\circ$ of latitude.

Figure 3. Lomb-Scargle periodicity plots from the spacecraft strip maps shown in Figure S1. The top panel plots the dates when the SED was absent (1995-1996). The middle panels shows the dates where the SED was present and the equatorial region filled with white clouds (2000 and 2008), and the bottom panel shows the dates when the SED was present, but the equatorial region was largely dark or reddened (1979 and 2007).

Figure 4. Chevron measurements from Hubble data. Top: manual chevron velocity measurements, plotted over longitude showing inherent velocity variations in individual features. Bottom: The latitude distribution of the chevrons measured in the top panel, with uncertainties plotted for 2008. The solid line is the Cassini zonal wind profile from Porco et al. (2003).

Figure 5. Correlation analysis from Cassini maps. Top panel shows results of the velocity correlation at 7.5° S. The redline marks the average velocity of 135 m/s, and the core of the SED is visible from $\sim 208^\circ$ to 220° W longitude. Bottom: Grey scale images overlain with color scaled correlation velocity values.

Figure 6. Motion of chevrons in 2008, when the SED was conspicuous. This JUPOS chart of ground-based shows measured longitudes vs. time for the chevrons. All dark spots between latitudes 6.0 and 9.0° S are plotted and the track of the SED is marked by a grey line. Timescale runs downwards, marked at the start of each month. L' , longitude in a system moving at $9.36^\circ/\text{day}$ in System III ($u = 134$ m/s for lat. 7.3° S; this is $-2.0^\circ/\text{day}$ in System I). The box at the top indicates the gradients corresponding to 3 representative speeds. Note how the tracks of chevrons begin slowly on the east side of the SED (e.g., dark grey arrows) then accelerate, so the fastest tracks are remote from the SED (e.g., light grey arrows). Images and enlarged tracks for some chevrons are shown in Suppl. Fig. S4.

Figure 7. Motion of chevrons in 2010, when the SED was absent. This plot is identical to Fig. 6, except for measurements made in 2010. Note that most points fall into long-lived clusters moving with $u \sim 158$ m/s (gaps between them are marked with large open arrows), and many individual chevrons move with similar speed (e.g., black arrows), but there are also short-lived chevrons travelling more slowly within these clusters (e.g., grey arrows). Images and enlarged tracks for some chevrons are shown in Suppl. Fig. S5.

Figure 8. Frames from a Cassini chevron movie. These maps span 7.5° N to 22.5° S centric latitude and 90° of longitude, and were chosen for approximately equal time separations. The longitude reference frame advances at 140 m/s in System III. The horizontal dashed lines mark 6.5° S centric (7.5° S graphic) latitude. Crests and troughs were identified from the movie and marked in each frame. The velocity and wavelengths are somewhat variable, but average about 20° in wavelength and 100 m/s in velocity.

Figure 9. Great Red Spot latitude variation over time. Historical values are those reported by Peek (1958, plus signs) and Rogers (1995, stars), and more recent spacecraft data, primarily Hubble, are shown as diamonds. All latitudes were converted to a common planetographic latitude system for comparison. Measurement uncertainties are unknown for the oldest data, $\pm 0.2^{\circ}$ to 0.5° for photographic data after 1950 and $\pm 0.1^{\circ}$ for spacecraft data. Grey regions indicate times when an SED is confirmed to have been present, including very brief periods around 1920 and 1950.

Supplemental Online Figures:

S1. Strip maps of Jupiter's 7° S region over time. Longitude strip maps from complete rotations of Jupiter. Each map is centered on 7° S planetographic latitude, and spans $\pm 5^\circ$ degrees of latitude and 360° of longitude. For each date, continuum red to near-IR wavelength images are shown (orange for Voyager) to maximize cloud deck opacity contrast between chevrons and thick clouds. The position of the SED is marked on each map, when present.

S2. History of the SED from 2004-2010. (a) JUPOS measurement chart summarizing chevrons and spot measurements. The track of the SED (purple and blue lines) is overlaid on the JUPOS chart of longitude vs. time for all features between latitudes 5.0° to 8.0° S. The longitude scale moves at $+1.0^\circ/\text{day}$ relative to System I ($-6.36^\circ/\text{day}$ relative to System III, or $+91\text{ m/s}$ for 7.3° S). The faint diagonal light blue line indicates 0° longitude in Sys. I. Both dark and bright features are shown: black = dark (mostly chevrons); red = white; + = spot; <--> = streak; < > = W and E ends. The track of the SED is either from visual identification when conspicuous (purple line), or from the W end of the blue-grey streak as tracked by JUPOS in other years (dark blue line). Dashed purple lines connect up the SED track between apparitions. In 2006 and 2007, the SED several times shifted $\sim 30^\circ$ to the E; in 2007, the double features persisted for a few months (mauve bands), before the new one expanded W to return to the original track. (b) Images of the SED in each year, including spacecraft images where available. Green arrows indicate the SED. When active and conspicuous, a single large arrow marks the edge of the rift into the SEB. When quiescent, 4 or 5 arrows mark its approximate extent, including the W end of the blue-grey streak and the E end of the long bright white strip, denoted by one or two curving projections. In 2007 the SED was double and both features are marked. (c) Diagrams of the typical aspect of the SED in its active and quiescent states. (A similar chart and image set covering 1999-2005 were shown in Rogers and Mettig 2008).

S3. Results from ground-based imaging in 2008. (a) Four images of the SED (indicated by green arrowhead). They include several dates on which it was connected by a bright streak ('rift') to the convective turbulent regions in the SEB. For measurement purposes, the longitude of the SED was defined as that of the preceding end of the darker segment along the northern SEB; its mean speed was $87.9 \pm 0.2\text{ m/s}$ from July to Nov. 2008. (b) Variation of speed with longitude relative to the SED. Speed scales are in m/s in System III (right) and in degrees per day in System I (left). Each horizontal line indicates the extent of a measured track segment and its mean speed. The speed gradient is best shown by the start points of the tracks (left ends), and closely matches the gradient found in 2000 and 2004 (Rogers and Mettig 2008). Means from these data are in Table 2.

S4. Example of tracking of chevrons in 2010 from ground-based images. (a) Images showing a train of chevrons in 2008 July. (Aligned on small NEBs projections which were moving rapidly at $\sim -2^\circ/\text{day}$ in System I.) Observers: I. Miyazaki (Japan), J.A. Soldevilla (Spain), K. Yunoki (Japan), G. Grassmann (Brazil). (b) Excerpt from the JUPOS chart (Fig.6) showing the same region. Green arrows indicate tracks of the 7 chevrons marked in the images. L' , longitude in a system moving at $-9.36^\circ/\text{day}$ in

System III ($u = 134$ m/s for lat. 7.3° S; this is -2.0 °/day in System I); the zero point in each panel is arbitrary. (c) Enlarged track of one of these chevrons, accelerating from $u = 119$ m/s to 128 m/s over one month. Inset, for comparison: Enlarged track of a faster-moving chevron remote from the SED, with $u = 143$ m/s.

S5. Example of tracking of chevrons in 2010 from ground-based images. (a) Images showing a chevron within a fast-moving cluster in September which suddenly decelerated on Sep. 21 (cyan line), alongside a chevron which persisted with rapid drift (black line). The images are aligned on typical dark projections on NEBs, which were almost stationary in System I. At this time the SEB was whitened; positions of belt edges are indicated. Observers: D. Peach (Barbados), P. Lawrence (U.K.), T. Akutsu (Philippines), C. Fattinanzi (Italy), P. Maxson (AZ, USA). (b) Excerpt from the JUPOS chart (Fig.7), showing the same cluster. Longitude scale as in Fig. S4. Arrows indicate the tracks of the chevrons marked in (a). The chevron immediately following (west of) these also seems to have decelerated at the same time, as indicated, although its appearance was more variable and its track less secure. (c) Enlarged track of the same decelerating chevron; speed changed from 151 to 139 m/s. Below, for comparison, enlarged tracks of a pair of chevrons elsewhere which maintained steady fast motion at 153 and 158 m/s.

Supplemental Online Material, movies:

Movie 1. Animation of Cassini/ISS near-IR continuum images of Jupiter between October and December 2000, prior to spacecraft flyby closest approach. Each frame spans 90° in longitude and 15° in latitude, with a central latitude of 7.5° S (planetocentric). The frame tracks eastward at 90 m/s, following the motion of the SED. The spatial resolution of the frames steadily increases as the spacecraft approaches the planet. Note that the time interval between frames is irregular.

Movies 2a/2b. Same as for Movie 1, except tracking a 90° swath of chevrons motions, co-moving at 140 m/s and with an initial longitude span of 0° to 90° W longitude. Features of interest have been annotated in Movie 2b.

Movies 3a/3b. Same as for Movie 2, except with an initial longitude span of 90° to 180° W longitude. Features of interest have been annotated in Movie 3b.

Movies 4a/4b. Same as for Movie 2, except with an initial longitude span of 180° to 270° W longitude. Features of interest have been annotated in Movie 4b.

Movies 5a/5b. Same as for Movie 2, except with an initial longitude span of 270° to 360° W longitude. Features of interest have been annotated in Movie 5b.