Jupiter's South Equatorial Belt cycle in 2009–2011: I. The SEB fade

John H. Rogers

A report of the Jupiter Section (Director: John H. Rogers), using data from the JUPOS team

Cycles of fading and revival of the South Equatorial Belt (SEB) are the most spectacular large-scale events that occur on Jupiter. The most recent started in 2009, when the SEB suddenly ceased its convective activity and began to fade. Modern amateur images, combined with measurements by the JUPOS team, have revealed several new insights into the process. The following phenomena were observed in this SEB Fade and in some or all previous ones: (1) Fading began within a few months after convective activity ceased. (2) As soon as the convective activity stopped, a series of dark cyclonic ovals ('barges') appeared in the SEB, suggesting reconfiguration of the retrograding jet. (3) The Great Red Spot (GRS) became isolated and increasingly red. (4) The GRS decelerated (*i.e.* increased westward drift). (5) As the SEB faded, a bright plume erupted intermittently to high-altitude on the north edge of the GRS, and induced a blue-grey streak preceding it. (6) A chain of faint spots developed all along the SEBs, constituting a wave-train with a drift rate less than full retrograding jet speed. (7) There was an outbreak of spots on the STBn jet. Some of these recurrent phenomena are not merely aspects of quiescence and increased cloud cover, but distinctive processes, indicating climatic conditions unique to the SEB Fade.

Introduction

Among the large-scale climatic upheavals that from time to time affect various belts on Jupiter, the best known and most impressive are the cycles of fading and revival of the South Equatorial Belt (SEB).[1–4] During the Fade, the normally dark SEB becomes calm and gradually lighter in colour, sometimes becoming completely white. Then the Revival begins at a single point from which vigorous disturbance spreads around the planet over several months. There were 15 such cycles in the 20th century, and so far two in the 21st. These cycles occur with unpredictable timing, sometimes with a periodicity of ~3 years but sometimes at much longer and irregular intervals.

The known characteristics of SEB Fades have been summarised as follows (see pp.169–170 of Ref. 2). The fading occurs over a matter of months, and persists for between one and three years before the onset of the Revival. If the SEB is not already double, the fading begins in the middle latitudes of the belt, but soon the southern component virtually disappears; this can occur within 2–3 months, or over a much longer period. In the era with 3-year periodicity, some fadings were not completed. The N component may remain as a dark though quite narrow belt, or it may fade also. The fading of the belt may not be entirely uniform; distinct, very dark streaks of SEB(S) may persist for several months.

The faded SEB can show a variety of pale colours. Bluish tint is common in the residual SEB(N), and occasionally in the faded SEB overall. Conversely, reddish colour is only seen in the faded belt when the coloration of the previous SEB Revival lingers during the next fading, or when the SEB(N) is involved with strong colouration in the EZ (though these conditions did not exist in 2009–'10). Sometimes there is a distinct bluish or grey triangle on the south edge of SEB(N) north-preceding (N*p*) the GRS. Bluish colour is thus common. As this colour is rarely seen at other times, it is evident that the fading is not merely a covering of the belt with white clouds.

During the fading of the SEB, the GRS intensifies, both in darkness and (often) in colour, to become a prominent dark reddish oval surrounded by the broad white zone (12 of 14 fades). Sometimes, rather faint bluish shadings develop around it. The GRS also usually decelerates (*i.e.* its drift becomes more westward). 'Detailed observations in recent well-observed fades showed that the GRS began to decelerate while the SEB was fading (1972) or even earlier (1988). So the deceleration is not a consequence of the visible changes, but an early and independent effect of the same underlying cause. When the SEB remains faint for several years, the GRS continues to deceler-

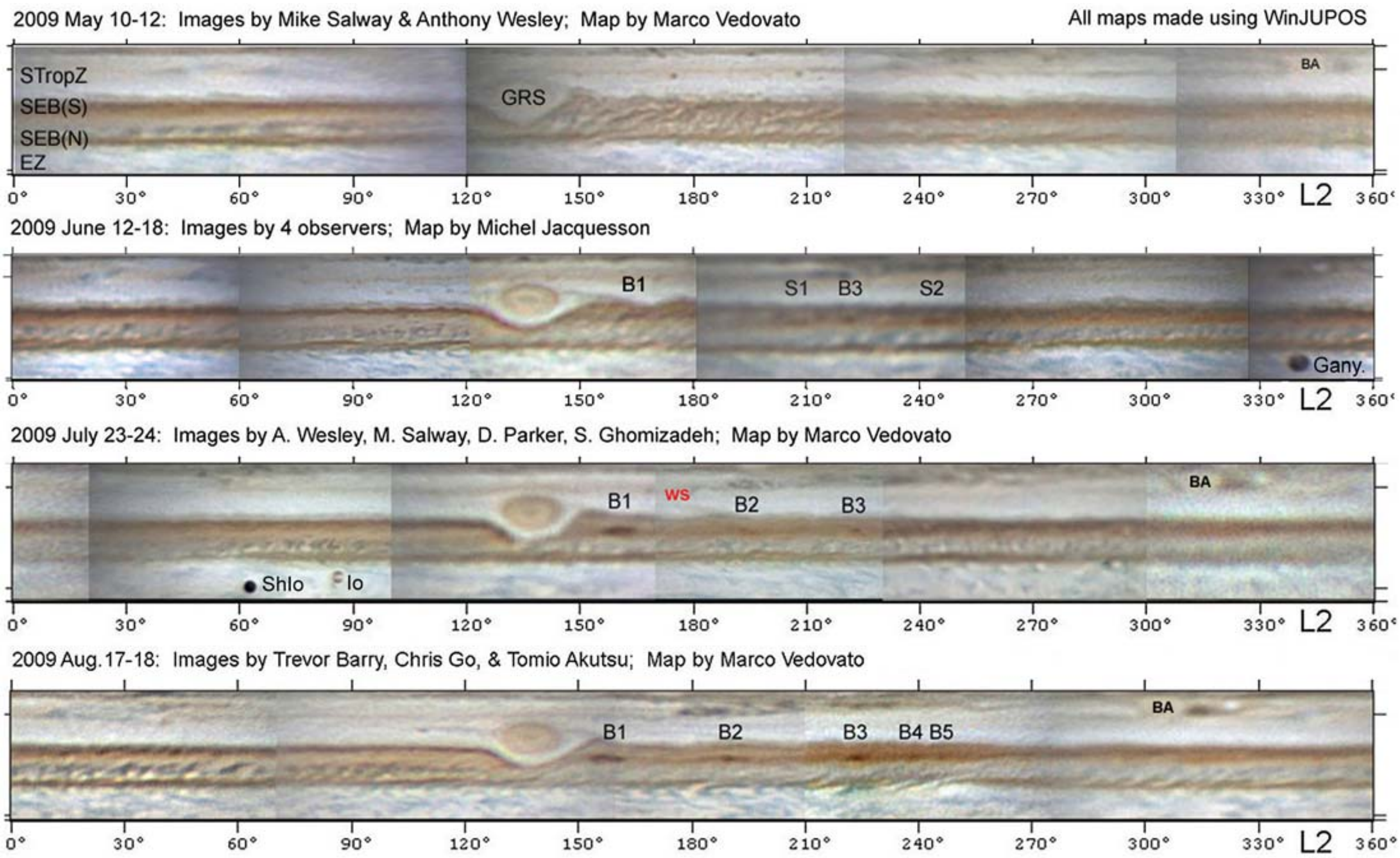

Figure 1. Maps of the SEB, 2009 May to August, showing the cessation of turbulent activity *f.* the GRS, and the formation of the barges (B1 to B5) and merger with pre-existing red streaks (S1, S2), as the SEB begins to fade. All maps were made using *WinJUPOS*.

ate throughout this period, by ~10^{-8} m/s^2 (~0.07°/mth^2) (1879–'82; 1926–'28; 1936–'38; 1972–'75). The continuing deceleration confirms that this state is not stable. The deceleration ends when the SEB revives.' (p.193 of ref. 2).

Since a series of SEB Revivals with a ~3-year periodicity ended in 1964, Revivals have occurred in pairs 3–4 years apart separated by much longer intervals: 1971 & 1975, 1990 & 1993, and 2007 & 2010. Thus the events of 2007 and 2010 were the first to be observed by amateurs with the intensive hi-res coverage that is now the norm. The 2007 cycle was short as the SEB had not fully faded when the Revival began, and the Revival had some unusual features because of the presence of a South Tropical Disturbance. The 2009–'10 cycle was more typical. (The Revival would begin on 2010 Nov 9.)

Both of these episodes have been described in detail in a series of reports on our website [**http://www.britastro.org/jupiter/section_reports.htm**]. For the 2007 cycle, these included a full final report,[5] and we also published a series of interim reports in this *Journal*.[6] For the 2010 SEB Fade, our description has been included in a paper in *Icarus*.[7] But our full observational results for the 2010 cycle have only been published online up to now.

In this pair of articles, I synthesise all the important results of the 2010 Fade (this paper) and Revival (following paper).

This paper covers the SEB Fade, from 2009 May to 2010 November. Full details have been presented in our online reports.[8–10] Two professional–amateur collaborative papers have achieved insight into the Fade in three dimensions: Fletcher *et al.*[7] integrated our visible-light results with thermal infrared data to analyse temperature and opacity changes, while Perez–Hoyos *et al.*[11] used visible-light images to model changes in the cloud layers.

Methods of observation and analysis

This report is based on images by numerous observers around the world. Full lists are posted on the BAA Jupiter Section website:

2009: **http://www.britastro.org/jupiter/2009reports.htm**
2010/'11: **http://www.britastro.org/jupiter/2010report25.htm**

and on the *JUPOS* website [**http://jupos org**]. We also used some images posted on the ALPO-Japan website [**http://alpo-j.asahikawa-med.ac.jp/Latest/index.html**].

Images were almost all taken using webcam selective stacking technology.[12–14] In these years, amateur coverage was becoming ever better, thanks to the large disk diameter, the increasing declination (allowing the numerous northern hemisphere observers to achieve first-class results), and the ever-improving technology (the Flea3 camera had recently been adopted by many observers). Consequently, the 2010 opposition was covered in tremendous detail by the global network of amateur observers.

The analysis is based on work by the *JUPOS* team: Gianluigi Adamoli, Michel Jacquesson, Hans–Jörg Mettig & Marco Vedovato. *WinJUPOS* was created by Grischa Hahn: see <**http://jupos.org**> and ref. 14. The team measured the images using *WinJUPOS* as usual, and produced charts of longitude *vs.* time for spots in all latitude ranges. For the 2009/'10 apparition they made a total of 56,492 measurements on images from 77 observers. For 2010/'11, they made 105,118 measurements.

Throughout this report, drift rates are given in degrees per 30 days in longitude system II (DL2). Where indicated, they are also converted to metres per second in system III (u_3). Prograde drifts are to the east (negative DL2, positive u_3); retrograde drifts are to

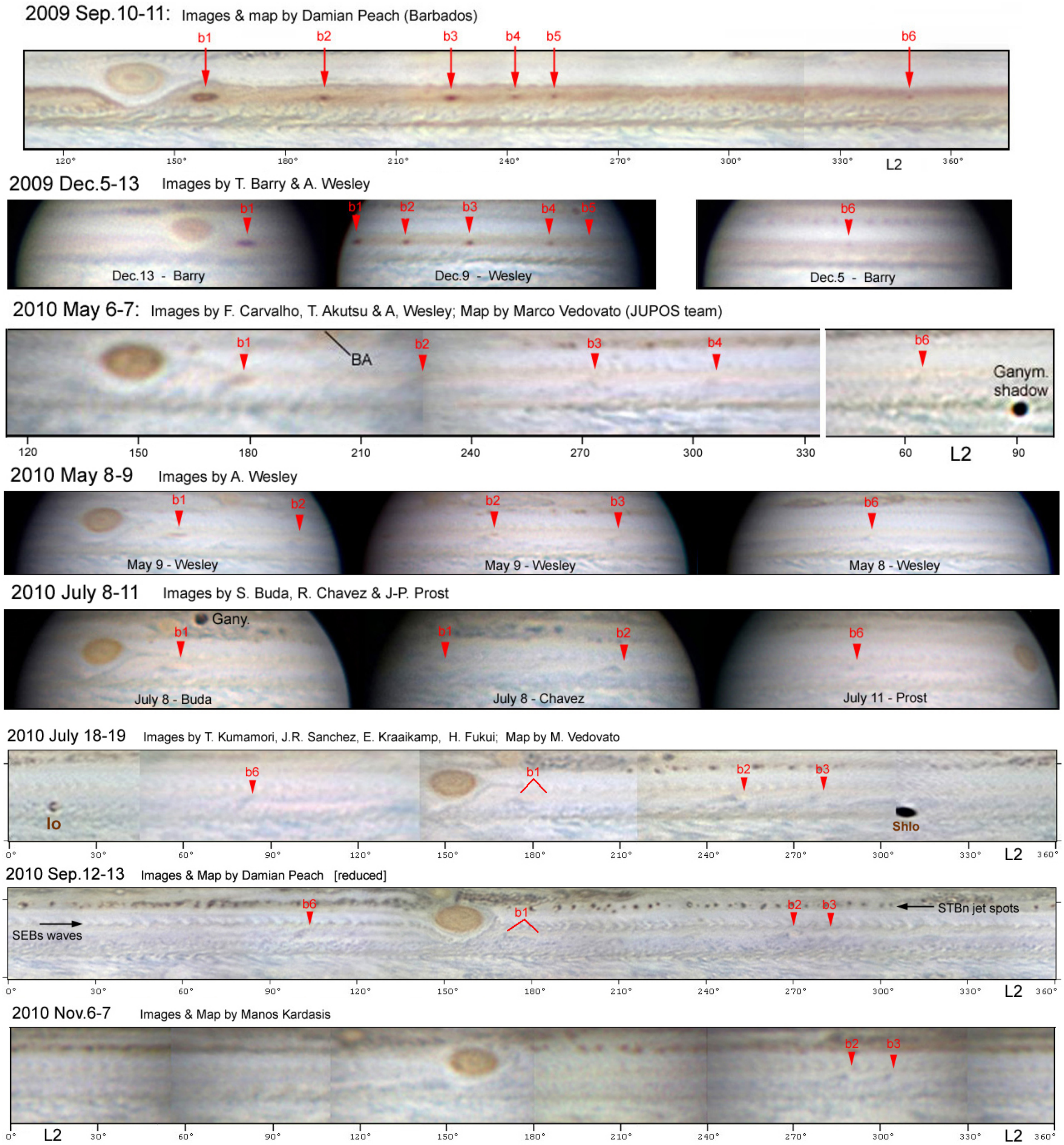

Figure 2. Maps of the fading SEB and barges (continued, 2009–2010). As the barges (red arrowheads) fade, a blue-grey patch appears on the N*p.* edge of each one. The STBn jetstream spot outbreak is also well shown.

the west (positive DL2, negative u_3). South is up in all images. P.= preceding= planetary east (left in images); F.= following= west (right). In *JUPOS* charts of longitude *vs* time, unless otherwise indicated, black points are dark spots, red points are bright spots. Latitudes are zenographic.

Results

The first sign of the change was the cessation of convective 'rift' activity in the SEB, in 2009 May–June. From June onwards, a series of cyclonic dark ovals ('barges') quickly appeared in order of increasing longitude, suggesting that there was a reconfiguration of the SEBs jet (Figure 1). Visible fading of the SEB(S) began in 2009 August, and the fade was well advanced by the end of the apparition in 2010 Jan. By that time, the five barges were very dark and obvious, and the GRS was a conspicuous orange oval detached from the belt. (Solar conjunction was in 2010 Feb.)

By the next opposition in 2010 Sep., the barges had also faded along with the belt, so the fade had proceeded almost to completion, more so than at any time since 1990, with the SEB almost absent and the GRS particularly red (Figure 2). In detail, the special phenomena of the Fade were as follows.

1. Fading began ~2 months after convective activity ceased

The post-GRS rift activity was mostly absent after 2009 May 26, though two bright spots near the GRS were still seen on June 5.

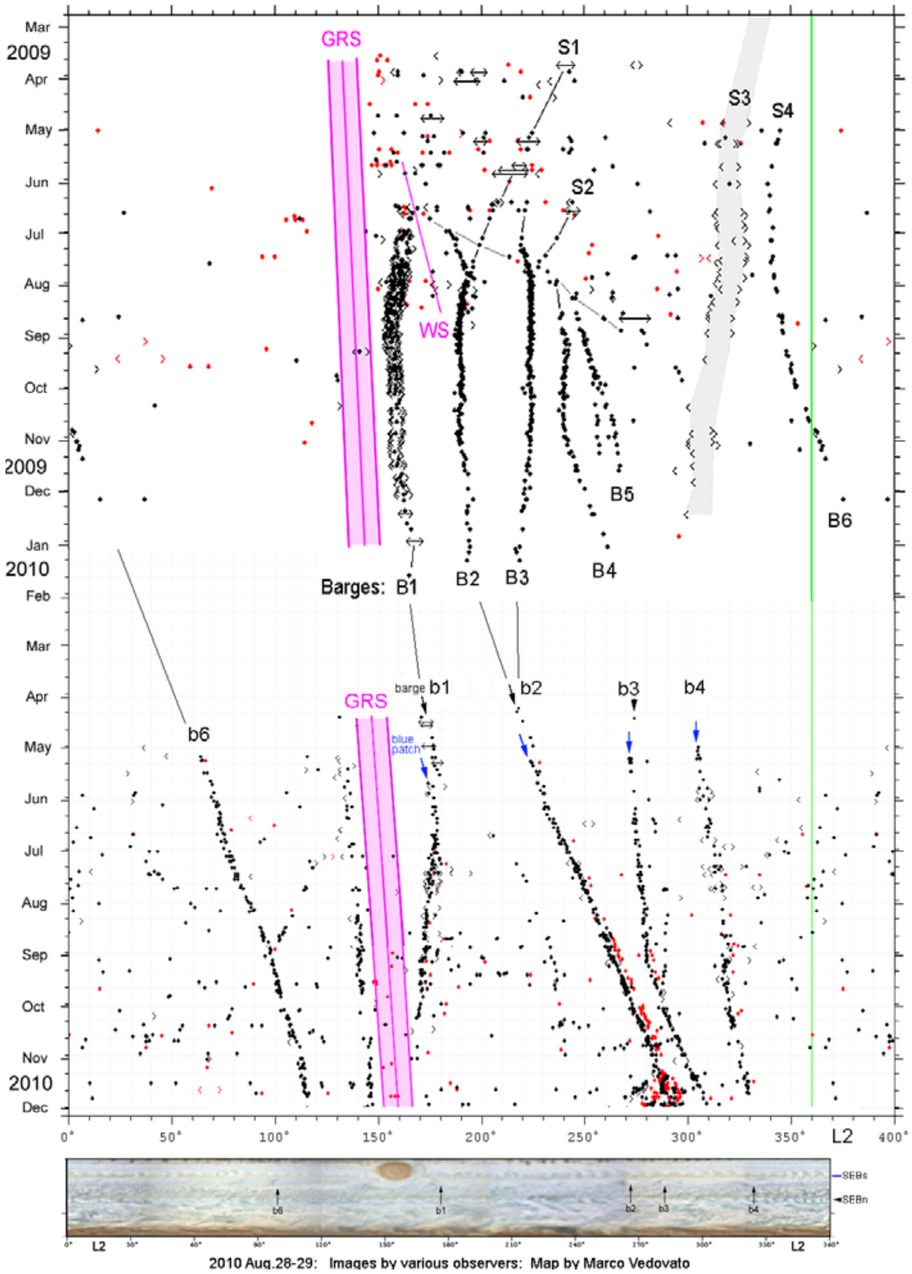

Figure 3. *JUPOS* chart of the southern half of the SEB. Upper (2009) (latitudes 18–15°S), showing the pre-existing red streaks S1 to S4, and the formation of barges B1 to B5 in order of increasing longitude. Lower (2010) (latitudes 17–14°S), showing the five barges. Barges B2 and B3 may have merged during solar conjunction, or one of them disappeared. In the months before the Revival, the remaining one (b2) had DL2= +10°/month. Black points, dark spots (including reddish barges and bluish spots); red points, white spots (notably barge b2 in late 2010). At bottom, map from 2010 Aug 28–29, aligned with the chart.

These were the last (Figure 1). With the cessation of the rift activity, the SEB(S) was quiet and undisturbed, and several observers suspected that the SEB would begin fading. As another consequence of the switchoff of SEB activity, the 'arch' connecting the GRS rim with the SEBs faded away at the start of July, leaving the GRS as an isolated though pale oval, which further reinforced our anticipation of a Fade.

Indeed, in August the SEB was visibly fading, and the barges which had already developed in it (see below) were strikingly dark. The SEB(S) (the major component) faded *f.* the GRS first, and the sector *p.* the GRS followed in October. By October, the SEB was fading quite rapidly, acquiring a pale orange tint. By the end of the apparition in 2010 Jan, although the SEB(N) remained a narrow dark grey band, most of the SEB had faded to a pale orange-fawn colour.

Fading proceeded during solar conjunction, and by the time of the next opposition, in 2010 Sep.,[9] the SEB was very faint across its entire width (Figure 2). It was not white; it was still easily visible to visual observers, and hi-res images showed a remarkable series of pastel-coloured components: greenish SEB(N), pale blue or mauve SEB(C), and beige SEB(S). (The earlier orange-yellow tint of the SEB southern half had faded.) The STropZ appeared greyish-white, but not as bright as streaks in the EZ.

2. As soon as the convective activity stopped, a series of cyclonic 'barges' appeared in the SEB, and later reversed contrast

The appearance of brown 'barges' (dark cyclonic oval circulations at 16–17°S) was a feature of this SEB Fade, suggesting reconfiguration of the retrograding jet. Up to 2009 May the dark broad SEB(S) comprised a dark grey southern strip and reddish-brown northern strip, and the latter was breaking up into several prograding dark red streaks at 16.4 (±0.3)°S (Figures 1 & 3: labelled S1 to S3). In June, as the SEB(S) became quiescent, these red streaks became more prominent, though some were shrinking.

The first new brown barge ('B1') appeared on June 15, just *f.* the GRS, alongside a white bay in the SEBs. Until June 30, B1 often had a tiny bright white spot in or around it, suggesting that it was a site of cyclonic turbulence, but then it settled down as a stable barge.

Four other small barges then appeared at progressively higher longitudes (Figures 1 & 3), as tiny dark red-brown spots: B2, B3 (already present but changed drift), B4, and B5. They were near-stationary, and slightly further south than the prograding red streaks S1 and S2, which shrank to tiny proportions and merged with B2 and B3 respectively in late July. The formation of these barges occurred along a track with DL2= +51°/mth from June 15 (origin of B1) to Aug 4 (origin of B5) (as sketched in Figure 3). Although there was no visibly retrograding feature on this track, it suggested a perturbation spreading along the retrograding SEBs jet, as discussed below. The barges were at 16.9 (±0.2)°S. By 2010 Jan, they were very dark brown and conspicuous.

During solar conjunction, either barge B2 or B3 disappeared, or these two barges merged. As this identification is uncertain we use numbers b1 to b4 for the first four in 2010 (Figure 3). The remaining dark brown barges faded in 2010 May, becoming invisible against the faded SEB (Figure 2a,b). However their outlines were still discernible, and blue-grey patches developed on their N*p.* edges. So in summer 2010, the barges were no longer visible as such, but the five blue-grey spots in the faded SEB marked their locations.

In late August, A. Wesley, A. Yamazaki and T. Mishina all drew attention to barge b2: not only had the blue patch become quite dark and conspicuous, but also the barge itself had become bright – especially in v-hi-res infrared images but also in visible light (Figure 4). It was close to barge b3 which looked similar though smaller. Barge b2 as a bright spot was centred at 16.8°S (±0.5°, SD; n=29), while the blue patch was ~3° *p.* it at 16.1°S (±0.4°; n= 35). (SD= standard deviation; n= no. of observations used.) This reversal of contrast was quite unexpected. As we wrote then: 'Such a phenomenon has never been observed before, but there has never been such hi-res study of this aspect of the SEB before. It is worth watching these barges as the SEB Revival outbreak could start in one.'[9] Indeed, it would start with eruption of a bright plume inside barge b2 on 2010 Nov 9.

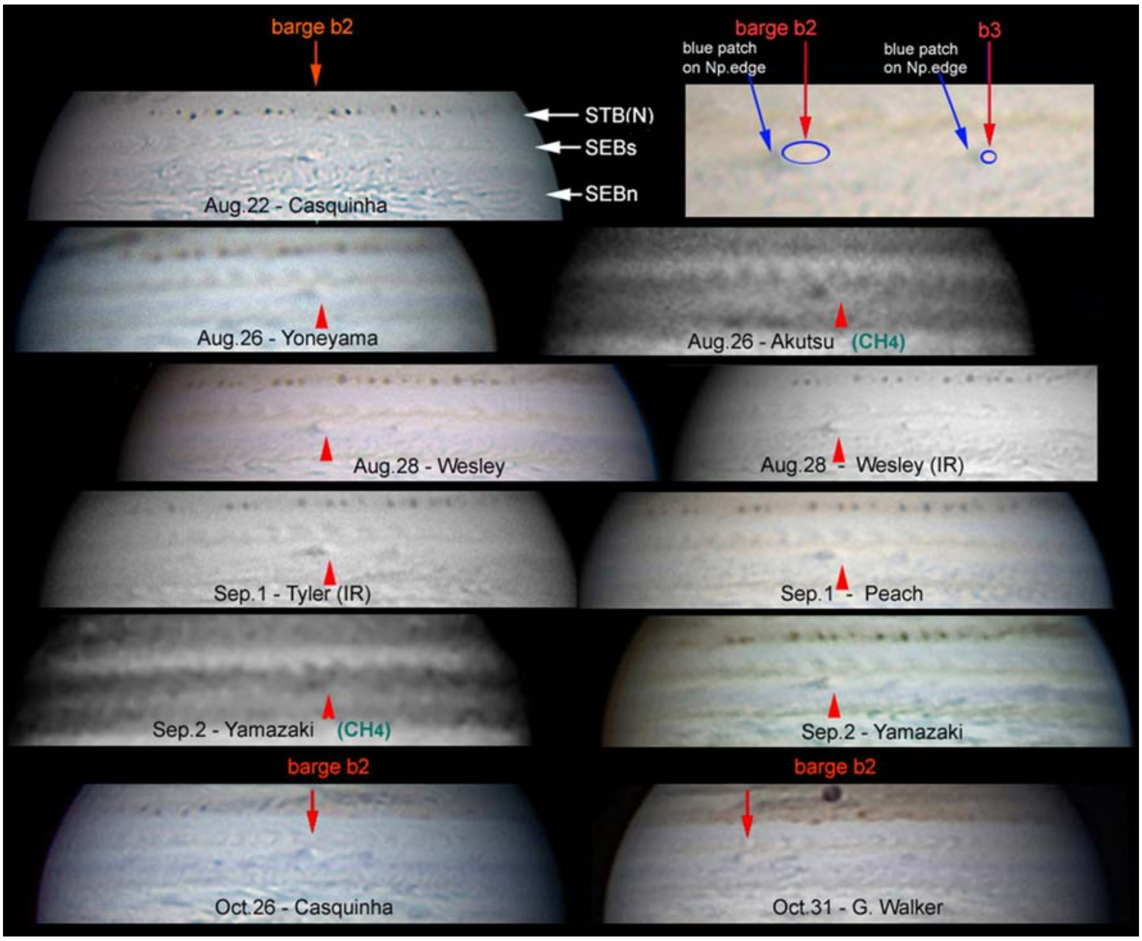

Figure 4. SEB barge b2 becomes bright, especially in infrared images. All images are in visible colour except for two in near-infrared continuum from ~0.7–0.9μm (IR) and two in the methane band at 0.89μm (CH4). The blue-grey patch on the *Np.* edge of b2 is prominent, and is dark in methane images (in which the barge itself is not visible). Barge b3 is similar but smaller. These features are labelled in the enlargement at top right (from the Aug 28 image). At bottom are images from late October, shortly before the SEB Revival began with a white plume inside barge b2. All images show the chain of small spots on SEBs. In the two methane-band images, it is more evident that the chain of spots is a wave separating the methane-dark SEB from the bright STropZ. *T. Mishina contributed to this compilation.*

3. As the SEB faded, the GRS became isolated and increasingly red.

By 2009 October, the GRS had become a well-defined isolated orange oval (already more so than in 2007). The colour continued to intensify and by 2010 September the GRS was strongly reddish, just as in the most notable previous SEB Fades such as 1973–'75, 1990, and 1993.

Superb hi-res images of the GRS were contributed by observers all around the world, and we posted some compilations of them (*e.g.* Figures 5, 7, 8).[15] These showed the motions of many small and faint spots in the currents around the GRS, including a loop on the *f.* side of the GRS on which a tiny dark spot from the STBn prograding jetstream circulated down to the SEBs (Figure 5). The loop then expanded into a broad faint blue collar around the *f.* side of the GRS, as was seen in the *Pioneer 11* images in 1974.

4. The GRS decelerated.

The GRS normally decelerates (moves towards higher longitude, *i.e.* DL2 becomes more positive) during SEB Fades, and this happened in 2009–'10 (Figure 6). The right-hand chart in Figure 6 shows the motion of the GRS from 2005 to 2011. The long-established 90-day oscillation is obvious throughout, with a period of 90.3 days over 19 cycles, not significantly different from previous values and unaffected by the Fade. Longer-term variations superimposed on this show clear deceleration during the Fades in 2007 and 2009–'10. From 2008 Feb to 2009 June, the GRS had a mean drift DL2= +0.8°/mth. But it then slowed down, drifting +1.2°/mth from 2009 June to 2010 June, while the SEB faded. It then decelerated still further to +1.6°/mth for the second half of 2010. (With the 90-day oscillation still operating, this meant that it moved +3° in some 30-day intervals, but only +1° in others.)

5. As the SEB faded, a bright plume erupted intermittently north of the GRS, extending to high altitude, and created a blue-grey streak *p.* it.

In 2009 October, on the N edge of the Red Spot Hollow (RSH), a remarkably bright white spot appeared, and the characteristic blue streak soon appeared *p.* it (Figure 7). A similar white spot (though not so brilliant) had appeared in 2009 April and July, as noted by M. Jacquesson. In 2009 October, compilations and analysis of the origin of the new white spot were made by M. Jacquesson, Y. Iga, T. Mishina, and C. Pellier[8] (Figure 7).

The spot most likely developed from an inconspicuous little white spot in the RSH (Sep 27), which then became a very bright spot interrupting the rim of the RSH (Oct 4–9), then moved fully into the adjacent narrow SEB (Oct 12). It then emitted a less-bright white streak *p.* it in the SEB, with the blue streak along its N edge (Oct 19–26). Remarkably, the white spot was also bright in methane-band images (Oct 12–28), as A. Cidadão and K. Yunoki pointed out, so it was a plume reaching high altitude. This seems to be the first report of a persistent methane-bright spot being present within a cyclonic belt. Conversely, the blue streak was methane-dark, indicating a clearing of the clouds.

This brilliant white spot reappeared in 2010 July (as pointed out by T. Mishina). Again it was bright even when very close to the limb (*e.g.* images by G. Tarsoudis, Aug 2), and bright in methane images. As further evidence that this was a vigorous little storm like a miniature SEB Revival, a narrow dark streak extended S*f.* from it around the Red Spot Hollow (RSH), sometimes including tiny dark spots, from mid-July to mid-August.[15] The white plume disappeared suddenly in early August, and was then absent throughout September, but there was still a bright white RSH. The blue streak or triangle N*p.* the GRS persisted throughout. The white spot then reappeared in 2010 October in the same manner, and again it was methane-bright (Figure 8).

6. A chain of faint spots developed all along the faded SEBs, with less than full jet speed, while several gaps in the chain moved with full jet speed.

From 2010 May onwards, all around the S edge of the fully faded SEB, the SEBs was marked by a regular chain of tiny white ovals alternating with very faint grey patches or projections, with a spacing of 5–7° (Figures 2, 4, 5, 11). This appearance resembled the SEBn with its chevrons, quite unlike the usual appearance of the SEBs jet with its turbulence and vortices. The chain of spots on SEBs developed at a late stage in the fading, when the clouds had already thickened substantially, as it was not present up to October 2009, but it was visible after solar conjunction from 2010 May onwards. It extended all around the planet, with spots emerging within a few degrees *f.* the Red Spot Hollow (RSH), and continuing until they slid into the RSH from the *p.* side. By thorough JUPOS measurements and analysis [*Footnote 1*], we were able to measure the drift rate for this previously unreported chain of spots; these were also the first speed measurements for the SEBs jet during a complete Fade. The results are in Figure 9 and Table 1. (In this section, 'fast' and 'slow' refer to speeds in the retrograding direction, *i.e.* westward.) *(Footnote 1)*†

In July, the mean speed at all longitudes was DL2= +75°/mth. From late July onwards, a sector of slower speeds gradually spread west from the RSH (Figures 9 & 10). This was largely due to newer spots having slower speeds, but also a group of spots ahead of them decelerated, and at higher longitudes still, slower spots emerged behind a gap (see below). Thus, by early Sep most spots were slow-moving. During Sep–Oct, speeds increased again for new spots arising *f.* the RSH, and so a new fast sector with DL2~ +74 spread westwards around the planet, until in November the speed was +70 to +74 almost everywhere.

Overall, we can assign a mean speed of +69°/mth and mean latitude of 20.7°S (±0.25°) for this chain of spots, both bright and dark. There were variations in both speed and latitude (see below), but they were not correlated. The spots did not show a coordinated speed change on approaching the RSH. The mean spacing was 5.5° (±0.2°) in the fast sector, and ranged from 5.7° to 7.3° in the slow sector.

The mean latitude was initially 20.8°S for the grey ('dark') spots or projections, both in fast and slow sectors, and 20.9°S for the bright spots. Over time, the latitudes did not change significantly in the sector *p.* the GRS (20.65°S in Nov), but were slightly lower at

Table 1. Latitudes & speeds of spots in SEBs wave-train

(A) Speeds & latitudes for all spots *[as in Reports no.8 & 24]:*

	L2	Dates	N	DL2 (deg/mth)	u3 (m/s)	Dark spots: Lat.	(Lat) SD	(Lat) n	White spots: Lat.	(Lat) SD	(Lat) n
July-Sep.	fast sector	July-Aug.	62	**75** (Range +70 to +82)	**-37.8**	-20.8	0.5	628	-20.9	0.5	295
	slow sector	Aug.-Sep.	50	**57** (Range +50 to +66)	**-29.6**	-20.8	0.5	280	-21.0	0.5	183
Sep-Oct.	all sectors	Sep.-Oct.	86	**~50 to 74**	**~-26 to -37**	(Not analysed in detail.)					
Nov. (undisturbed sectors)	20-140	Nov.1 - Dec.3	37	**74**	**-37.3**	-20.7	0.4	321			
	230-380*	Nov.1-25	26	**71**	**-36.0**	-20.4	0.5	233	-20.4	0.4	119
	*See box below for details.										
	230-380	Nov.1-8	8	72	-36.4	-20.5	0.4	73	-20.4	0.5	65
	320-380	Nov.9-29	9	72	-36.4	-20.5	0.4	83			
	290-330	Nov.10-15	6	70	-35.5	-20.1	0.5	53	-20.2	0.3	16
	310-360	Nov.16-25	3	70	-35.5	-20.5	0.5	24	-20.5	0.4	38

Notes:
(A) covers all spots, although precise measurements were only made on the better-defined ones, and not at all in October.
(B) covers only the sectors with the most uniform spacing and speeds, to establish the wave parameters.
N = number of tracks measured for dark spots in these group(s); in some cases, more were present but not so well tracked.
DL2 = drift rate in L2 in degrees per 30 days. u3 = wind speed in L3 in m/s, as calculated from DL2, for lat. 20.0 S.
Latitudes are averages over all spots in range. Uncertainty for latitude is standard deviation (SD); n = number of measurements.
In (B), estimated uncertainties are given. For the spacings of waves, the number of intervals measured was usually N-1.

(B) Speeds & spacing for the most regular wave-trains *[as in ref.16]:*

Dates	DL2 (deg/mth)	+/-	u3 (m/s)	+/-	Spacing (deg)	+/-	N
July	**80**	8	**-40.1**	3.6	**5.3**	0.8	11
July-Sep	**75**	4	**-37.8**	1.8	**5.5**	0.2	37
Aug-Sep	**50**	1.5	**-26.4**	0.7	**7.3**	0.25	14
Sep	**60**	1.5	**-31.0**	0.7	**6.7**	0.25	7
Nov	**71**	1.0	**-36.0**	0.5	**5.5**	0.15	8

† *Footnote 1:*
The SEBs spots were measured by the JUPOS team: M. Jacquesson, H-J. Mettig, G. Adamoli & M. Vedovato. The data were then re-plotted on a large scale using Microsoft *Excel*; tracks of spots were identified, and drift rates were measured for 112 track segments over intervals of 4–16 days between July 16 and Sep 5. These were all tracks of dark features (pale grey spots/projections), as the JUPOS team measured these more often than the bright spots between them, but the bright spots simply alternated with them and therefore had the same parameters.

A similar analysis was performed for November (63 track segments). The data for September and October (86 track segments) were not analysed in detail but clearly had the same properties. Lengths of tracks were usually limited by gaps in the data and slight variations in drift rate; many of them probably persisted for at least 30 days.

The analysis was not straightforward, for several reasons. The features were small and faint, so they could only be tracked on hi-res images. They were indistinguishable spots spaced 5–6° apart in a continuous chain, so we needed closely-spaced sequences of hi-res images to establish the approximate drift rate and to overcome aliasing. These measurements had to be plotted on charts with high temporal resolution. To complicate the analysis further, there were sectors with different speeds.

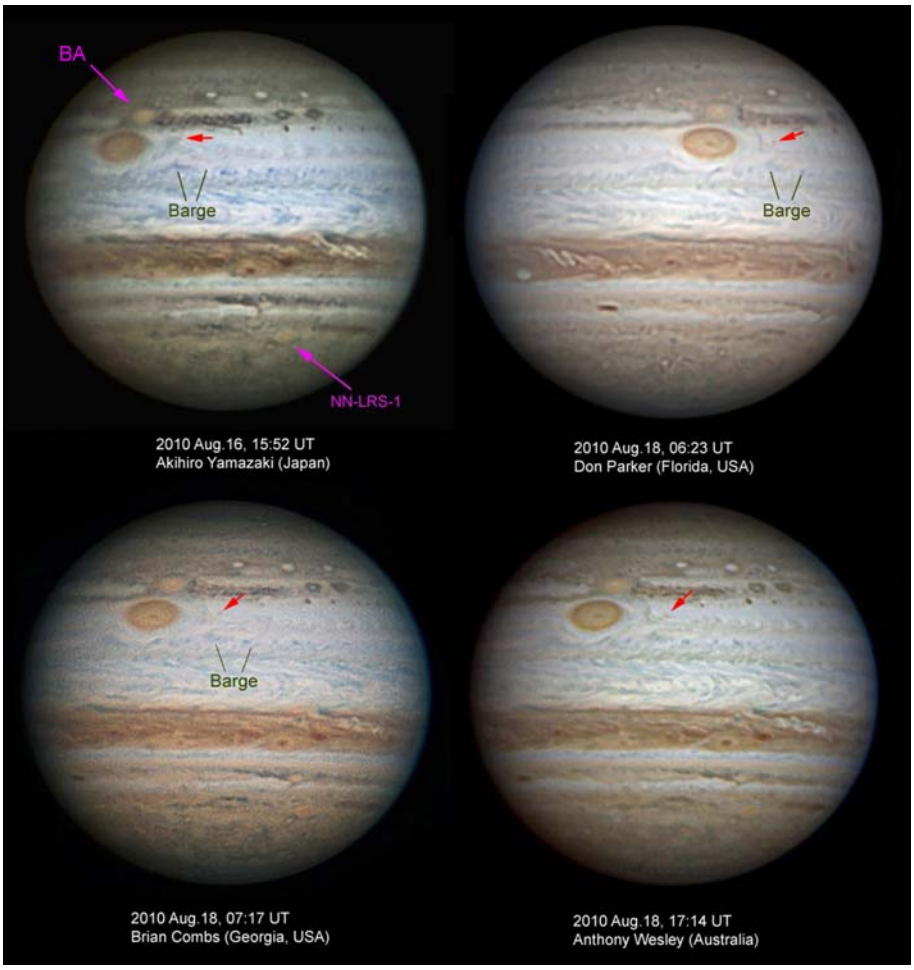

Figure 5. V-hi-res images of the planet showing the GRS, 2009 Aug 16–18. Barge b1 is labelled 'Barge'. Red arrow indicates a tiny dark spot from the STBn recirculating down to the SEBs, while the adjacent dark cusp of SEBs forms a complete arc up to the STBn *f.* the GRS. Anticyclonic red ovals BA and NN-LRS-1 are also marked. The lower pair of images, taken 10 hours apart on Aug 18, can be 'blinked' to show motions all over the planet.

lower longitudes, averaging 20.4°S in Nov, and as low as 20.2°S in one sector (Table 1). (While the standard deviations are ~0.3° to 0.5°, the standard error of the mean is always <0.1° because of the large number of measurements; see Table 1.) At these latitudes, the slow speeds were significantly discordant from the mean zonal wind profile (ZWP). Moreover, it now appears that the principal feature was a wave-train on the peak of the SEBs jet at 19.5–20°S, marking the northern edge of the chain of spots. This is indicated by the appearance in professional thermal-infrared images, which emphasised the wave-train,[16] and in hi-res methane-band images, in which the SEB was still dark (Figure 4). Most conclusively, we observed wave-trains on SEBs in subsequent years, and there was a tight linear relationship between the wavelength and the speed, applicable both in 2010 (Table 1, part B) and in subsequent years.[16]

There was another unexpected and remarkable finding. There were several short gaps in the chain of spots, which retrograded much faster, at DL2= +134 (±6)°/mth (Figure 9). This is the same as the peak speed of the jet in other years (see Discussion). Few spots were tracked across the gaps. Images showed them as stretches with either no spots or only faint traces of them, and no coherent structures of their own (Figure 11). These gaps were still evident up to November, still with DL2~ +132 to +140°/mth.

The chain or wave-train persisted with little change until the onset of the Revival – indeed, even thereafter, it persisted in sectors that were not yet directly affected by the Revival, until the dark spots of the reviving SEB(S) actually overran it. This did not occur until December in some sectors.

7. There was an outbreak of spots on the STBn jet.

From 2010 May onwards, there was a substantial outbreak of small dark spots in the STBn prograde jet, emerging from the *p.* end of a dark STB segment.[17,18] A second outbreak *p.* oval BA started abruptly in 2010 July, which was apparently a consequence of a collision of STB structured segments;[17,18] but the earlier outbreak had no visible cause, having developed during solar conjunction in early 2010 (see Figures 2, 8, 11). It may have been connected with the concurrent fading of the SEB (see Discussion below). So in autumn 2010, the STBn had an unprecedented high density of dark jetstream spots all around the planet.

Discussion: Positive features of the fading of the SEB

The events in 2009 revealed or confirmed several consistent features of the fading phase of the SEB cycle. These discoveries indicate positive phenomena in a phase which is otherwise characterised by absence of visible disturbance. All of them have been observed at some, if not all, previous SEB Fades, as listed in Table 2 and discussed below.

1. *The cessation of turbulent 'rift' activity f. the GRS* (in 2009 May–June) was rapidly followed by the onset of visible fading of the SEB, just over 2 months later (in August). This confirms the connection that had been noted in 1988/'89 and in 2007. In 1988/'89,[19] rifting ceased in 1988 Nov, and fading began ~5–8 months later during solar conjunction, some time between 1989 April and July. In 2006/'07,[5] rifting ceased during solar conjunction, some time between 2006 Sep and 2007 Jan, then fading began ~2–6 months later, in 2007 March. In 2009, we had the advantage of following the process continuously.

Table 2. Characteristics of the SEB fades in 2009–'10 and earlier years

Have these phenomena been recorded in previous SEB Fades?	
1. Fading begins soon after convective activity ceased:	Yes (1989, 2007)
2. Cyclonic 'barges' appear:	Sometimes (2007)
3. The GRS becomes isolated and redder:	Yes (usually)
4. The GRS decelerates:	Yes (usually)
5. A bright plume erupts N of the GRS (intermittently) and creates a blue-grey streak *p.* it:	Yes (1990, etc.) Yes (often)
6. A chain of faint spots develops along SEBs: moving more slowly than jet peak.	Yes (1974, 1990, 1993)
7. STBn jet spot outbreak:	Sometimes (1927, 1969)

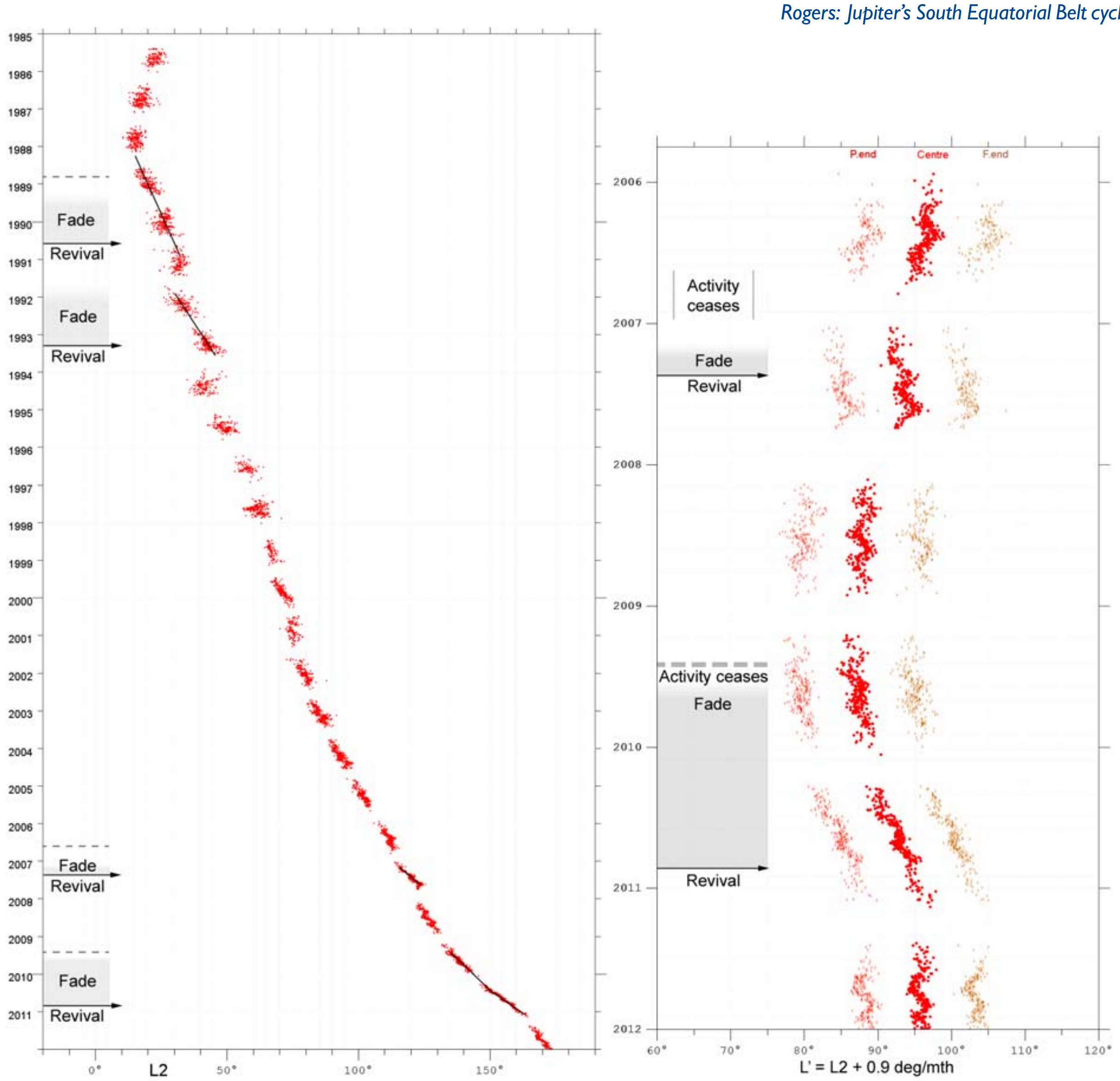

Figure 6. *JUPOS* charts showing the motion of the GRS, 1985–2011. *Left:* in System II longitude, 1985–2011. Up to 1998, almost all measurements were visual transits, with 3° added to correct the mean transit error. (This mean error was determined in years when both visual and image measurements were available.) From 1999, almost all are image measurements. The tracks during SEB fades, when the drift is more positive, are marked.
Right: in a longitude system moving at –0.9°/month relative to System II, 2006–2011. Timecourse of SEB fades and onsets of revivals are indicated. The 90-day oscillation has been strictly maintained throughout, with superimposed deceleration (trend towards higher longitudes) starting in 2009. *Charts by courtesy of Hans–Jörg Mettig.*

From mid-infrared observations sensing atmospheric temperatures, Fletcher *et al.*[7] showed that an anomalous cool strip had already developed in mid-SEB by 2009 July, even before obvious visible fading, so this may have been the proximate cause of the enhanced cloud formation in subsequent months which gradually whitened the belt.

2. *The formation of 'barges'* at progressively higher longitudes may represent a reconfiguration of the retrograding SEBs jet. When the rifted region *f.* the GRS is active, the jet usually carries turbulence and often vortices; and indeed in 2008 it was highly turbulent. After the switchoff of activity, the lack of disturbance and the visible smoothness of the SEBs suggest that the jet became smooth-flowing; I speculate that this allowed an imperceptible meandering to develop, giving rise to the barges as eddies on its north side.

   Small barges likewise appeared during the SEB Fade in 2007.[5] Isolated barges have occasionally been recorded in earlier fades:[2] quite long dark streaks in 1926, 1959–'60, and 1989 (possibly similar to barge B1), and smaller dark spots in 1949 and 1993. However the visual record does not determine whether barges are a common feature. They have not been recorded in most fades, but they might have been missed due to their small size, or due to loss of contrast. The whitening of the barges in 2010 rendered them invisible, although their persistent outlines indicated that they still persisted as cyclonic circulations.

3. *The GRS becomes isolated and redder:* This behaviour has been observed in almost every SEB Fade, even in the 19th century.[2]

   Under normal circumstances, turbulence and vortices on the SEBs jet are entering the RSH and often generate a dark rim around the GRS, as shown in the *Voyager* movies. During a Fade, the turbulence and vortices disappear, and this appears to be why the GRS becomes separated from the SEB.

   This may also explain why the GRS becomes redder, as the *Voyager* movies showed that the incoming turbulence was disrupting the red cloud cover. However, the nature of the red aerosol has for long been a mystery. Very recently it was reported to match the spectrum of material produced by ultraviolet irradiation of ammonia and acetylene, which are present at different levels in Jupiter's atmosphere, but likely to be mixed and exposed to solar ultraviolet where there are high clouds due to an updraft.[21]

4. *The GRS decelerates.* This has been observed in almost every SEB Fade, if the duration was long enough and if the GRS drift was not confounded by interaction with a South Tropical Disturbance.[2]

The chart (Figure 6) shows a deceleration even during the brief SEB Fade in 2007, and much more so during the longer fade of 2009–'10. In both cases it started at about the same time that the convective activity ended, before the visible fading began. Also, the deceleration continued in 2009–'10 as the fade progressed, as is normal during prolonged fades (see Introduction), although on this occasion the duration was not long enough to measure a consistent deceleration rate.

I suggest that the change in drift rate occurs because the normal convective activity exerts an eastward force on the GRS. We recently discovered that oval BA, the second largest anticyclonic oval on the planet, always moves more rapidly eastwards when there is a dark, turbulent sector of STB *f.* it, and decelerates when this STB segment shrinks to a small quiescent dark spot.[17,18] The nature of this 'force' remains to be explained; we do not know whether it is a direct eastwards force, or whether the turbulence acts like a wedge to displace the oval southwards into a zone with faster zonal wind speed, as oval BA does move southwards when it accelerates. In the case of the GRS, we did not detect any significant change in latitude (>0.3°) during the SEB Fades in 2007 or 2009–'10. Another possibility is that the end of convective activity alters the latitudinal wind profile across the RSH so that the speed is changed even while the GRS itself remains at the same latitude.

However, this hypothesis does not explain why the GRS continues to decelerate throughout the Fade. This behaviour suggests that the SEB Fade is not a stable state.

5. *The bright spot and blue streak seen N of the GRS* are now revealed to be connected, and both comprise a recurrent feature of the fading phase of the SEB.

The blue streak or triangle N*p*. the GRS has been noted many times when the SEB is faint (see Introduction) (p.170 of Ref. 2). It appeared again in 2009.

The bright spot was more surprising. Bright interruptions in the RSH rim are common in normal times, but are believed to result from retrograding vortices being torn apart in the RSH, which cannot apply at present. However, identical white spots were observed along with the developing blue streak as the SEB faded in 1989–'90 and 1992–'93, and during each of those Fades the white spot and/or the blue triangle came and went several times within a year. In fact, in 1989/'90 we reported the same connection with the blue streak.[20] The blue streak was conspicuous in 1989 July & Nov, 1990 Feb, and April–May, but faint in alternate months. Hi-res photos showed that the streak in 1990 Feb extended rapidly *p.* from a bright white spot due N of the GRS over a few days, developing 'like a miniature SEB Revival'.[20]

The parallels with an SEB Revival, both in 1989–'90 and in 2009–'10, are a bright white plume extending to high altitude,

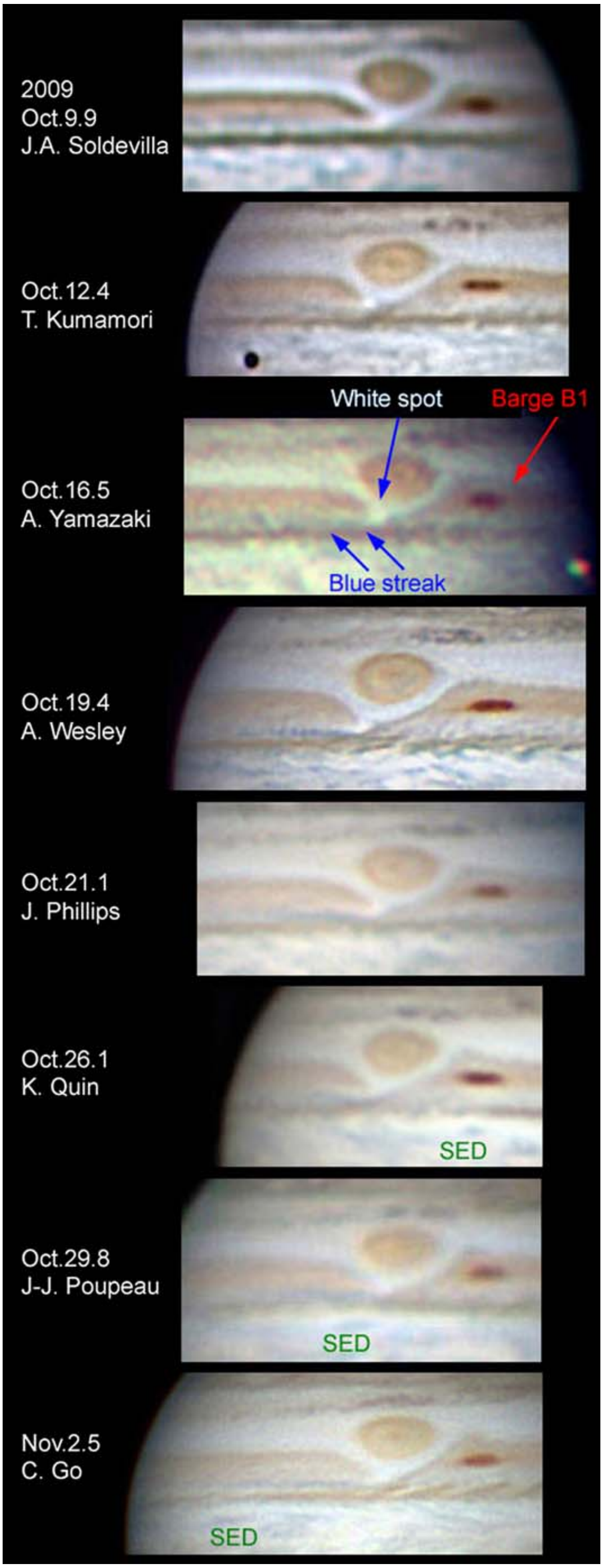

Figure 7. Appearance of a bright spot and blue streak N of the GRS as the SEB fades. Also marked is the South Equatorial Disturbance (SED) passing the GRS. *M. Jacquesson and the ALPO-Japan contributed to this compilation.*

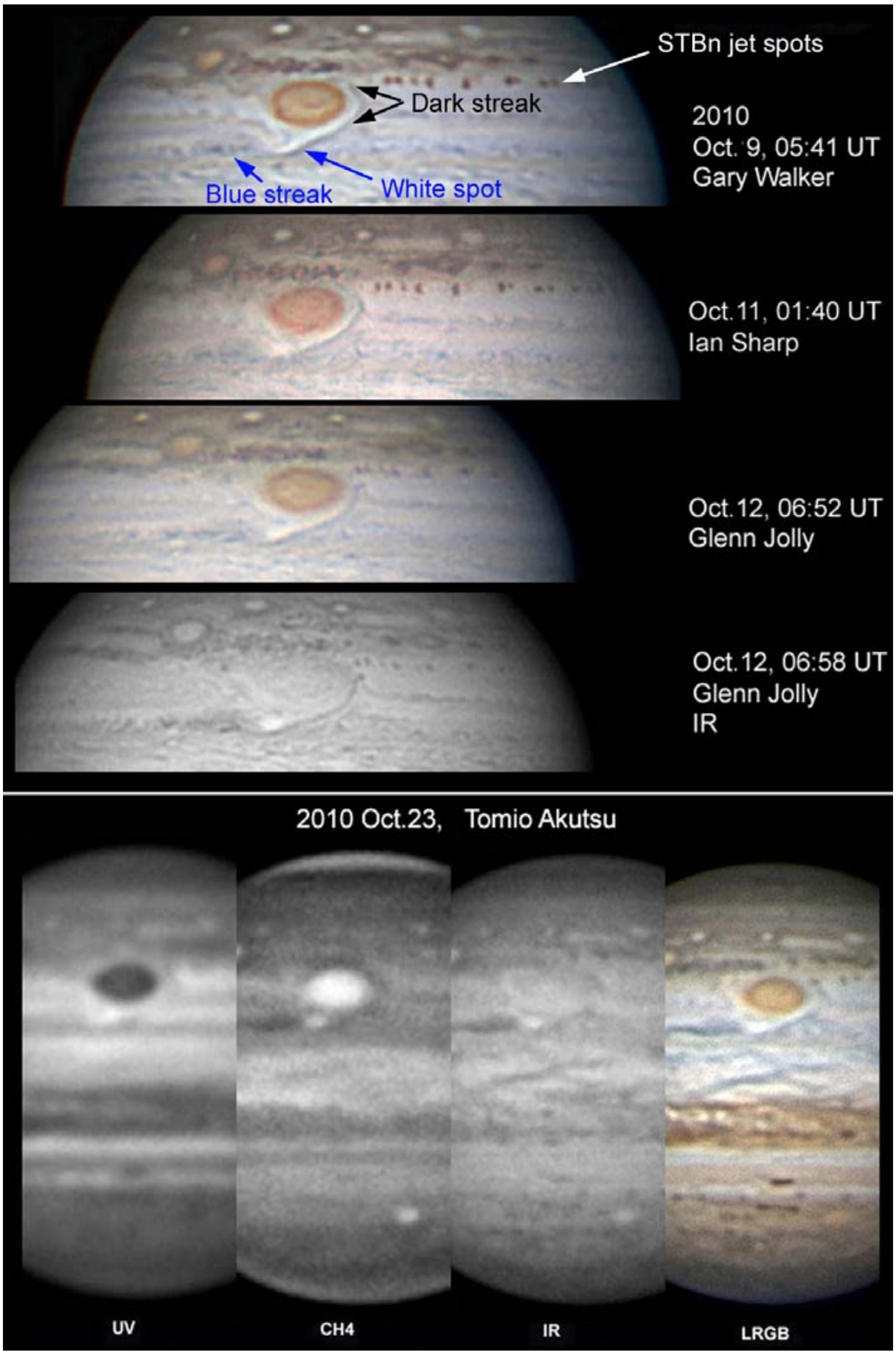

Figure 8. Reappearance of the white spot N of the GRS and blue streak *p.* it, 2010 Oct. *Bottom:* Multispectral images by *T. Akutsu*: ultraviolet, methane band, infrared continuum, and visible colour.

and a disturbance spreading *p.* from it, in the form of a white streak with a bluish streak on its N edge; and in 2010, disturbance extending S*f.* from it as well. The bluish streak or triangle, which is methane-dark, is presumably a patch from which clouds have been cleared by this miniature outbreak. As this bluish triangle is a persistent and common feature of SEB Fades, it is likely that the white plume is also a common feature, but previously went unobserved visually because it is intermittent and because of limited resolution.

6. A chain of faint spots develops along SEBs, moving more slowly than jet peak: Inspection of the few v-hi-res images available from previous SEB Fades shows that the pattern was also present during complete Fades in 1962, 1974, 1990 and 1993 *[Footnote 2a]*.‡ However it was not visible in 2007 nor 2009, suggesting that it only appears when the SEB fading is complete.

The most surprising aspect was the slow retrograding velocity of the chain of spots, as compared to the normal jet peak velocity in almost the same latitude. (In this section, 'fast' and 'slow' refer to speeds in the retrograding direction, *i.e.* westward.) Our measurements in 2010 are the first for the jet itself in the fully faded state, and for the chain of spots on it, as imaging in previous Fades had not been adequate to measure these speeds *[Footnote 2b]*. ‡

The peak speed of the SEBs jet was determined as DL2=+128°mth by *Cassini* (u_3=–62 m/s),[23] and +133°/mth (u_3=–64.5 m/s) by *New Horizons*;[24] the latter agrees with our determinations in recent years.[16] However, the ZWPs from spacecraft were all obtained during normal (non-Fade) conditions of the SEB, except *New Horizons* which was at the very beginning of a Fade [*Footnote 3*].§

In 2010, we found three lines of evidence that the peak jet speed was still high despite the Fade and the slow-moving chain. First, we observed gaps in the chain moving with DL2~ +134 °/mth. Second, a ZWP was obtained by Grischa Hahn from amateur images on 2010 Sep 4,[25] with DL2=+94 (u_3=–46.6 m/s) for the peak of the jet at 20°S. Although slower than usual, this was much faster than the concurrent speed of the chain. Third, when the SEB Revival began, dark spots in the SEB(S) immediately started to move with full jet speed of +132°/mth [Ref 10 & Paper II], suggesting that this jet speed was present throughout. Thus it appears that the peak speed and latitude of the SEBs jet are essentially unchanged during an SEB Fade. In principle, from the 2010 observations alone, it could be that the slow-moving chain of white spots was at higher altitude than the main cloud deck, where the jet velocity would be less. Alternatively, they could be a wave-train within the main jet, with a phase speed much less than the wind speed of the jet.

‡ *Footnote 2:*
(a) As we have noted elsewhere,[7,16] the SEBs wave pattern was imaged by *Pioneer 11* in 1974 Dec[22] and by the Observatoire du Pic du Midi in 1962 Sep [**http://www.lesia.obspm.fr/BDIP/index.php**], 1990 Jan. [Figures 5 & 6 of Ref. 20] and 1993 April [Figure 4 of Ref. 3].
(b) There were drift rates for single spots retrograding just *f.* the GRS while the SEB was faint in 1962 (DL2= +68 –> +34°/month; ALPO) and 1971 (DL2= +54.5; NMSUO).[2] They did not necessarily represent the zonal current globally.

§ *Footnote 3:*
The *New Horizons* spacecraft observed a peak jet speed of DL2= +133.4°/mth (u_3= –64.5m/s),[24] for indistinct streaks along the SEBs. Independent autocorrelation analysis of the same images by Grischa Hahn, while obtaining a slower mean speed overall, confirmed ~+130°/mth in some sectors.[25] These images were taken in 2007 Jan, when SEB activity had ceased; but visible fading had not yet begun, and the situation was complicated by the recent appearance of two South Tropical Disturbances, which might have altered the jet dynamics.

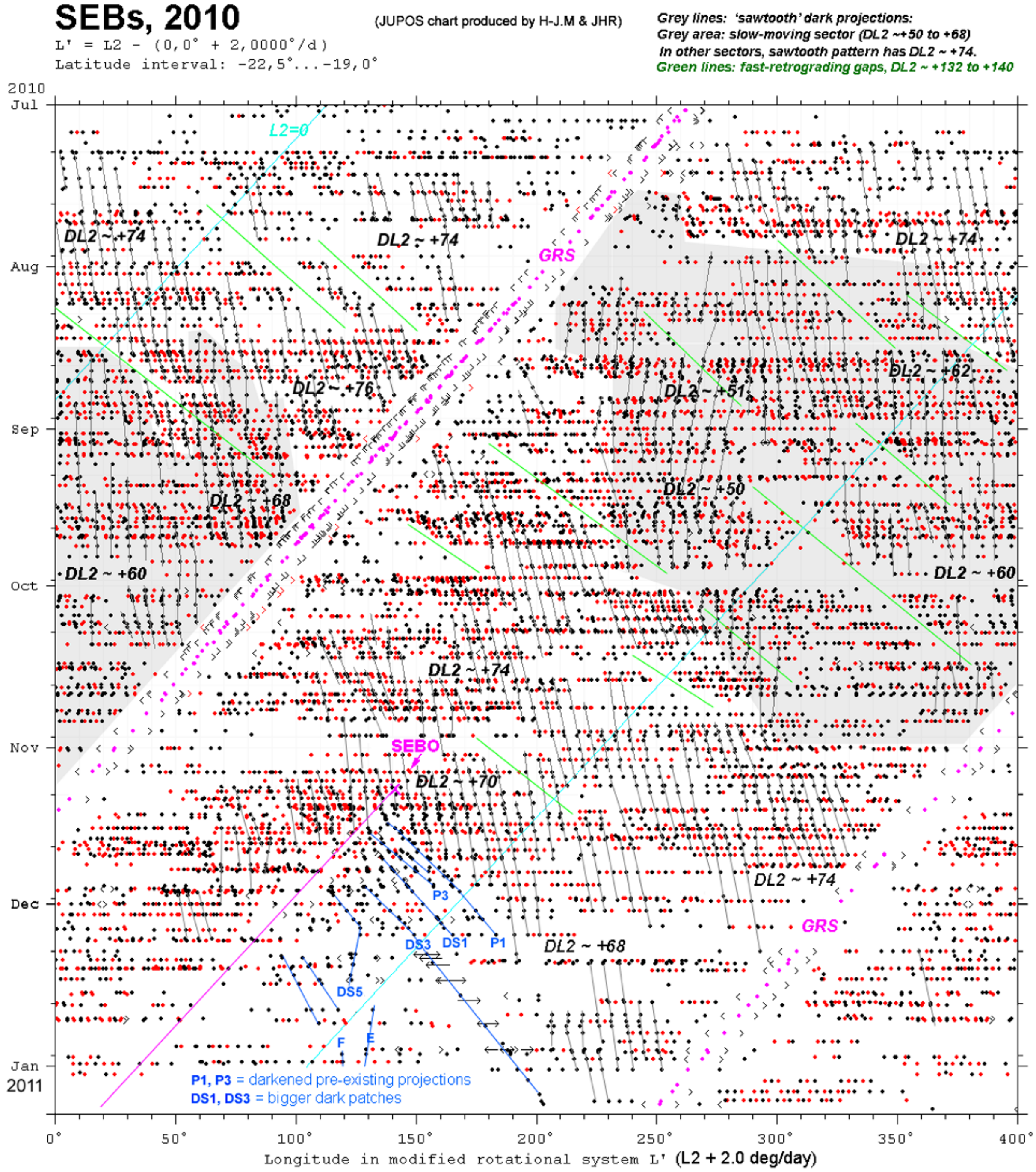

Figure 9. *JUPOS* chart showing the motion of the chain of spots on SEBs up to the Revival. It shows all dark spots (black) and bright spots (red) on the SEBs (latitude band −22.5 to −19.0°S), in a longitude system moving at +2.0°/day relative to System II. Grey lines indicate tracks of the dark projections. Mean drift rates of different sectors are marked. The grey area is the slowly-retrograding sector with DL2~ +50 to +68°/mth; in other sectors the chain had DL2~ +70 to +76°/mth. Green lines indicate fast-moving gaps with DL2~ +132 to +140. Blue lines and labels indicate the first dark spots in the southern branch of the SEB Revival, after the initial outbreak (SEBO). Cyan line indicates L2= 0. *Base chart by courtesy of Hans–Jörg Mettig.*

The latter hypothesis has been validated by professional infrared observations, and by our observations in subsequent years: we have again observed wave-trains on the SEBs which move much more slowly than concurrent spots with peak jet speed in overlapping latitudes.[16] This wave pattern develops along the SEBs jet in very different states of the SEB – before, during, and after the SEB Revival – but mainly when the jet has little other disturbance. We have analysed it thoroughly elsewhere.[16] So the chain of spots during the SEB Fade can be understood as an outstandingly regular example of this remarkable wave phenomenon, and does not entail a change in the speed of the jet.

7a. An outbreak of spots on the STBn jet: Such outbreaks, representing instability of the prograding (eastward) jet, are generally observed in only two circumstances:

(i) as spots recirculated from the SEBs jet at a South Tropical Disturbance;[2] or

(ii) (from 1998 onwards) after a structured STB sector collides with the slower-moving anticyclonic oval BA.[17,18] (There are also small and sparse spots on the jet in most years, only detectable by hi-res imaging, as reported by the New Mexico

State University Observatory (NMSUO) in the 1960s[2] and by our team since 2000.[17,18] They are negligible compared to the two major categories.)

The outbreak in early 2010 stands out as the only outbreak in recent years which could not be accounted for in these two major categories; and there is reason to suspect that it was connected with the concurrent fading of the SEB. Before the era of modern imaging, likewise, the only observations of STBn jetstream spots that did not fit into the above categories were during SEB Fades [pp. 215–'16 of Ref. 2]. The most substantial was an outbreak in 1927'28. Single spots were observed in 1940/'41, 1941/'42, and 1962. And whereas the NMSUO recorded sparse spots throughout the 1960s, those during the SEB Fade in 1969 may have been more numerous.

Another possible example was in early 1993, when the previously absent STB revived rapidly in several segments, and a few images suggested possible STBn jet activity.[4] The record before 2000 may well be incomplete as, in many years, STBn jet spots could have been missed due to inadequate resolution or due to masking by a dark STB. On the other hand, there have certainly been SEB Fades when no such outbreak occurred (*e.g.* 1972–'75). The known outbreaks are too few to establish a definite relationship to SEB Fades, but are highly suggestive.

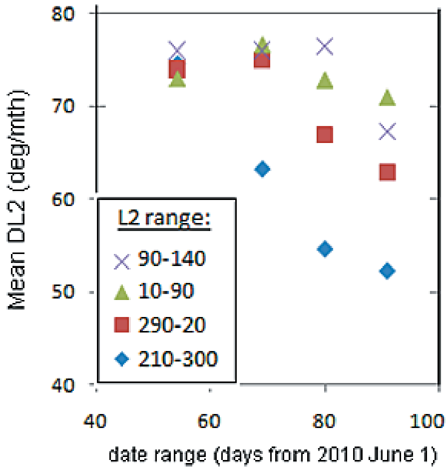

Figure 10. Spread of the slow sector along the SEBs. Mean speed for the chain of spots in each longitude sector is plotted for four time intervals. The sector *f.* the GRS decelerates first (L2 210–300), followed by sectors at higher longitudes.

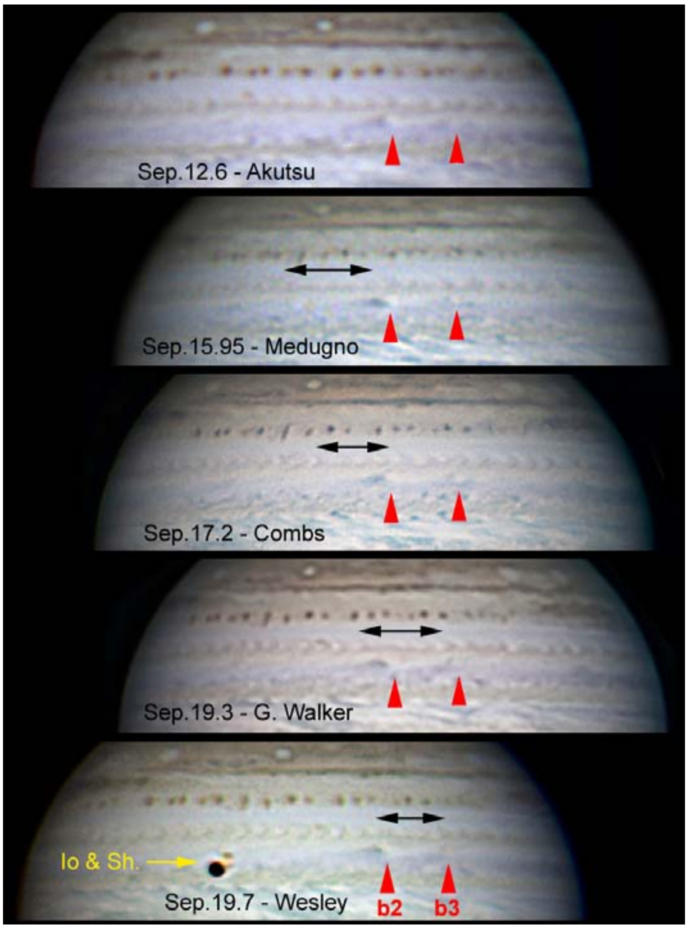

Figure 11. The chain of faint spots on SEBs, with one of the rapidly retrograding gaps (indicated by black bar). The locations of barges b2 and b3 are indicated by red arrowheads. STBn jetstream spots are also well shown.

7b. South Tropical Disturbances? In addition, we should mention one other phenomenon, which was not present in 2009–'10: the development of a South Tropical Disturbance (STropD: a dark sector of the STropZ produced by recirculation between the jets flanking the zone). The possibility of a link with SEB Fades was suggested by W. Wacker[26] in his formulation of what we now call global upheavals, but such a link was by no means certain. Indeed, the first five SEB Fades of the 20th century did all coincide with STropDs: the great STropD up to 1939, then the dark S. Tropical Streaks which emerged *p.* the GRS in 1941–'42 and 1946–'47.[1,2] But during the next six SEB Fades, at ~3-yearly intervals, only one STropD was recorded (1955–'57), and it was not synchronised with the Fade (1956–'58). Subsequently, though, there have been several rather faint STropDs which developed specifically during SEB Fades, in 1970–'71, 1993, and 2007 (two) – though not during the Fades of 1973–'75, 1989–'90, and 2009–'10.

This phenomenon has been discussed in the accounts of 1993[4] and 2007.[5] We have proposed that it represents an increased tendency for recirculation from the SEBs jet southwards into the STropZ, as part of the overall change in meteorology before and during the Fade.[5] This could be related to the tendency for barges to appear on the north side of the SEBs jet, as both phenomena could arise from subtle long-wavelength meanderings of the jet. Thus the SEB Fade may have dynamical consequences right across the S.Tropical Zone, in the form of either a STropD or a STBn jet outbreak.

Conclusions

The SEB Fade in 2009–'10 has been better observed than any previous example. We have reported several distinctive phenomena during it, and shown that each of these has been observed in some or all previous Fades when conditions have allowed (Table 2).

The first sign of the imminent Fade is the cessation of large-scale convective activity in the SEB, which leads to disappearance of the usual disturbance on the SEBs jet. The GRS starts to decelerate at about the same time. As the SEB quietens, small brown barges sometimes develop in it, probably indicating a reconfiguration of the SEBs jet. Dynamical changes may also propagate from the SEBs jet into the STropZ, either creating a STropD (although this did not happen in 2009–'10) or triggering disturbance on the STBn jet. A few months after the rifting has ceased, the visible fading begins, *i.e.* thickening of whitish clouds within the belt. It was during those preliminary months that a cool SEBZ was observed within the belt,[7] presumably a key part of the meteorogical transition.

The progressive whitening of the belt and reddening of the GRS could be regarded as passive consequences of the cessation of convection, and the consequent cooling of the belt and condensation of clouds. However, other common features that we have reported appear to be positive changes during the faded state: the barges, the white plume north of the GRS which partly clears the cloud cover from a bluish triangle, and the circum-global wave-train on the SEBs. These are new meteorological features, which indicate that the faded state is much more than a simple covering with white cloud.

Address: 'Capella', Mill Hill, Weston Colville, Cambs. CB21 SN9. [jrogers11 @btinternet.com]

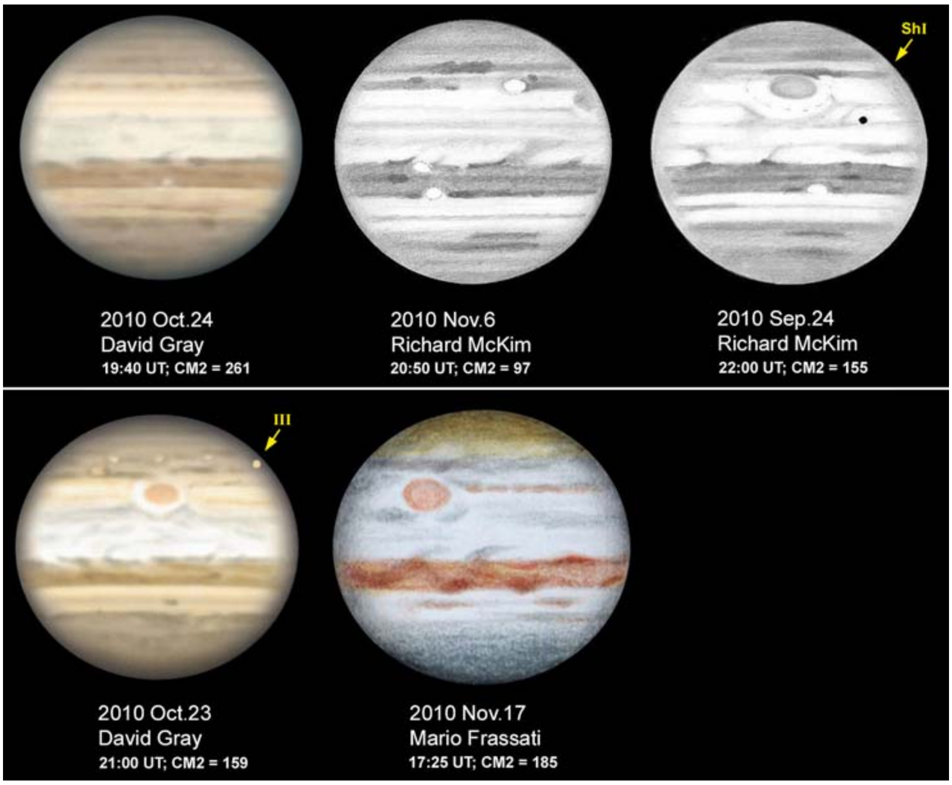

Figure 12. Drawings by visual observers showing the faded SEB and intensified GRS in 2010. *David Gray* (County Durham, UK) used a 415mm Dall–Kirkham Cass. with apodiser screen. *Richard McKim* (Northants, UK) used a 410mm Dall–Kirkham Cass. *Mario Frassati* (Italy) used a 203mm SCT.

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