2019 Feb.11

Jupiter's South Temperate Domain, 2015-2018

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*This report represents results from many observers, and from the JUPOS team, and from the JunoCam team – to all of whom I am very grateful. The JUPOS team are: Gianluigi Adamoli, Michel Jacquesson, Marco Vedovato, Rob Bullen, Hans-Jörg Mettig, and Grischa Hahn. The JunoCam team are: Candy Hansen, Glenn Orton, Tom Momary, Mike Ravine, Mike Caplinger, and Gerald Eichstädt.

This report describes the changes in the South Temperate domain from 2015 to 2018, as observed in ground-based images and in maps from Hubble and Juno. The dynamical features and previous history of this domain were described in our previous long-term reports for 1991-1999 [ref.1], 2000-2012 [ref.2], and 2012-2015 [ref.3]. Our final report on this domain for 2014/15 was included as an Appendix in the latter report [ref.3] so is not fully covered here.

Section 1 gives an overview of these three years.
Section 2 summarises data from cylindrical maps of spacecraft images, which have been plentiful in these years and could be exploited further. From the Hubble Space Telescope, pairs of maps 10-20 hours apart are made annually by the OPAL project [ref.4 & https://archive.stsci.edu/prepds/opal/)], and single or paired maps have been made on other dates by the WFCJ project [ref.6 & https://archive.stsci.edu/prepds/wfcj/]. From Juno, southern-hemisphere maps are made from JunoCam images, usually every 53 days since 2016 August [https://www.missionjuno.swri.edu/junocam/processing; https://www.britastro.org/section_front/15].
Section 3 reviews our ground-based results, all from amateur ground-based images unless otherwise stated. Most of this information has already been posted in our reports on the BAA web pages [https://www.britastro.org/section_front/15], along with many illustrations. (In quotations from previous reports herein, figure numbers and references in black or green type refer to the original report, not this present one.)
Appendix A is our new analysis of wind speeds in a cyclonic circulation called the STB Ghost, first in its quiescent state (from Hubble maps), then during its dramatic transformation in 2018 Feb.

In this report, unless stated otherwise, drift rates are in System II longitude (DL2, deg/mth = degrees per 30 days) and latitudes are planetographic. P. means preceding (east), f. means following (west). Maps and images have north up, which is our standard from 2015 onwards. However, JUPOS charts are still presented with longitude increasing from left to right, as if aligned with south-up maps, to maintain continuity with previous years and to avoid the confusion that would arise by reversing the chart orientation. **Appendix B** contains comprehensive JUPOS charts in both L2 and L3.

1. Overview

This domain is distinctive in its longitudinal segmentation **(Figures 1 & 2)**. It always has two to four structured sectors (with major cyclonic and/or anticyclonic structures) separated by undisturbed sectors [ref.2]. From 2015 until early 2018, it had no visually striking features. There was no dark South Temperate Belt (STB), just a whitened domain with three inconspicuous structured sectors (none of them dark), and no STBn jetstream spots. The three structured sectors were:

(1) Oval BA and the small dark spot f. it. Oval BA still had its orange colour, usually quite strong. The dark spot f. it, which had been turbulent and contracting, was small and largely quiescent. With the decline of this spot's activity, oval BA had decelerated to a speed typical of this quiescent condition.

(2) The STB Ghost (STB Structured Segment E). This was a cyclonic circulation, appearing as a pale blue loop, but methane-dark - just like the former Segment C (STB Remnant).

(3) The STB Spectre (STB Structured Segment F): a duplicate of the STB Ghost. This arose in early 2015 as a very dark cyclonic spot, which faded to pink in early 2016. In May it completed its fading to white as expected, leaving just a pale bluish loop around it, which persisted and was methane-dark, like the STB Ghost. So it was named the STB Spectre.

The Ghost and the Spectre, although cyclonic, affected the whole width of the domain, and blocked any spots approaching them on the SSTBn jet from the west. These spots would recirculate anticyclonically, due south of the Ghost or Spectre, and return westwards in the STZ for tens of degrees. This circulating track became visible as an orange-tinted 'recirculation loop' Sf. the Ghost and the Spectre.

Typical drift rates [refs.2 & 3], in DL2 (deg/mth) are as follows:
Oval BA when dark spot f. it is quiet: -10.4 to -11.8.
Oval BA with dark turbulent STB f. it: -14.2 to -16.5.
Structured sectors such as STB Ghost and Spectre: -15.4 to -17.8.

Their speeds from 2016 January to mid-May were typical: Oval BA, DL2 = -11.0 (±0.5) deg/mth, though with some fluctuations; STB Ghost and Spectre, both DL2 = -16.4 (±0.3) deg/mth, and therefore moving towards oval BA. From mid-2016 June to early 2018, BA had a mean speed of -12.0, with ~2-month oscillations, while the Ghost and Spectre proceeded with typical speeds.

Two dramatic events affected the domain in early 2018. Coincidentally, both began on 2018 Feb.4:
i) The STB Ghost collided with the small dark spot at the f. edge of oval BA, as predicted [ref.5], and a bright spot (convective plume) suddenly erupted inside it, initiating a turbulent transformation of the whole Ghost into a chaotic dark STB segment adjacent to oval BA. This also had all the other effects typical of these collisions, viz. oval BA developed a dark rim and accelerated, and dark spots were emitted p. on the STBn jet and f. in the STZ.
ii) A South Tropical Disturbance (STropD) arrived at the f. edge of the Red Spot Hollow, and turbulent material from it promptly began streaming around the S side of the GRS. Much of this accumulated in the S. Temperate domain Sp. the GRS, and a long sector became filled with tiny vortices. However, this all dissipated by summer 2018, with no lasting effect.

We previously noted that new cyclonic circulations and other spots tend to arise tens of degrees p. oval BA, but in these years, only small transient spots have appeared; no new structured segment has developed. The present count of two structured segments (the complex with oval BA, and the Spectre) has existed in some previous years, but it seems likely that a new structured segment will appear in 2019 – unless the STB revives more generally in some unexpected manner, as happened in 1993.

2. Results from spacecraft data

In our earlier long-term reports [refs.2&3], we presented evidence that the STBn jet has two components, of which the southern one is spatially and temporally variable: it is strong along the northern edge of dark turbulent STB sectors, but weak or absent in blank, undisturbed sectors. This has been abundantly confirmed since, by studies of Hubble data from earlier years [ref. 1] and later years [refs.1&6]. Wind speed measurements, both ground-based and spacecraft-based, are summarised in the **Table in Appendix A.** Also, Hubble and Juno images in 2015-2018 revealed the cyclonic circulations of the STB Ghost and Spectre clearly enough to obtain the first measurements of winds in these structures.

2.1 Observations from Hubble

(i) *From [Ref.6]:* Tollefson et al., 'Changes in Jupiter's Zonal Wind Profile preceding and during the Juno mission'

This paper presented wind speeds derived from pairs of Hubble maps on five dates: not only zonal wind profiles (ZWPs), but also (for the first time) global 2D maps of velocity deviations from the ZWP, in which major circulations are highlighted by contrasting colours. One of the most interesting regions was the S. Temperate region, where the paper confirmed our previous finding of longitudinal variability in the STBn jet, and circulation of the STB Ghost and Spectre.

EXCERPT:

"*Figure 14* plots the STB ZWP for each epoch. The variation in this region consists mainly in the presence or absence of a sub-peak at 29°S, and we find that it appears to correlate with the presence of a dark STB segment at 29–32°S. The 29°S sub-peak was present in 2008, 2009, and 2012 (hemisphere A), where such a STB segment was present, and not in 2012 (hemisphere B) nor 2016, where the STB segment was absent. In 2015, the 29°S sub-peak was not visible in the global ZWP, despite the presence of a short STB segment 19 degrees long just west of oval BA; however, the map of residuals (see *Figure S3*, velocity residuals for 2015) shows a strong eastward anomaly at 29°S precisely alongside this segment (and indeed, rapid circulation around the segment). These results confirm the report of Rogers et al. [ref.2], who likewise inferred that the 29°S sub-peak was conspicuous only in sectors containing a dark STB segment, from both HST and ground-based data in 2009 and 2012."

[Zonal mean speeds from this paper are included in the **Table** in our Appendix A.]

The STB Ghost shows up as a prominent cyclonic circulation in the maps of 2015 Jan.19 (Fig.S3) and 2016 Feb.9 (Fig.6); and the Spectre as a weaker feature in both; i.e. these maps confirm the observations in [ref.1] quoted in (ii) below. The colour-coding indicates that wind speeds along their N and S edges are faster than the zonal jets. The colours are only semi-quantitative, but suggest speeds of at least ~40 m/s on the N edge and ~30 m/s on the S edge, similar to my new measurements in (iii) below.

(ii) *From our report [Ref.1], Part III:* 'Circulation in and around the STB Remnant/Ghost/Spectre: HST pairs in 2009 Sep., 2015 Jan., 2016 Feb.'

EXCERPT:

Since 2003, some STB structured segments are not dark and turbulent, but are pale oblique loops which appear to be cyclonic circulations: segments C (the STB Remnant), E (STB Ghost), and F (DS5, --> STB Spectre?). But ground-based images are not sufficient to demonstrate their circulation. Here we show these 3 features in pairs of HST images or maps taken ~10 hours apart on 2009 Sep.18-19, 2015 Jan.19, and 2016 Feb.9-10 (Fig.5). By 'blinking' the images, one can see evidence for the expected cyclonic circulation, clockwise around the pale blue loop, in each case.

In addition, we have repeatedly observed anticyclonic hemi-circulation of small spots due south of these structures, from the SSTBn jet to the STBs jet. However, this is not evident in the general flow of the jets in the first two image pairs; this may indicate that the structure is a barrier to discrete spots but not to the background wind flow. However, in the second image pair there is an oblique streak marking an albedo boundary which appears to mark the path of recirculation, and in the third pair, anticyclonic motion can be seen at this point. These images are therefore consistent with previous inferences from ground-based observations.

(iii) New estimates of winds in the STB Ghost from paired Hubble maps.
I have now measured wind speeds in the STB Ghost from the paired Hubble maps of 2017 Feb.2; one map is shown in **Figure 3**. ***Details are in Appendix A1.***

The STB Ghost shows very high speeds on both N and S sides, by both methods. On the N side, the speed along the visible N edge (43.8 m/s, 30.0ºS) is not the fastest: faint features further N have an average of 57.5 m/s at 29.3ºS. On the S side, the streaks on the visible S edge have the fastest speed, -35.4 m/s at 32.3ºS. These velocities are much faster than recorded in ZWPs for undisturbed STB, and are in the same range as for turbulent dark segments of STB, so the quiescent STB Ghost is similar to those turbulent segments in its wind speeds. During its subsequent transformation (see below), its wind speeds did not change much except that some features on its S edge moved even faster (as also observed for the STB Remnant transformation in 2010).

2.1 Observations from Juno

At each perijove (PJ), JunoCam takes v-hi-res images of areas visible during the low-altitude pass, and it usually also takes a series of outbound images which cover most or all of the southern hemisphere south of the SEB. All the images are posted by the JunoCam team on their web site [https://www.missionjuno.swri.edu/junocam/processing]; each image is projected into maps by Gerald Eichstädt, and these are merged into combined cylindrical maps by JHR. In some sectors the outbound maps have higher resolution than ground-based maps, and they give good coverage when the planet is invisible from Earth. The combined maps are posted on the JunoCam web site and in reports for each perijove on the BAA Jupiter Section web site [https://www.britastro.org/section_front/15].

At its first 17 perijoves, JunoCam has covered all sectors of the S. Temperate domain, at resolution rivalled only by the very closest Voyager and Galileo images, and with notably better image quality. One surprising finding is the widespread occurrence of small bright shadow-casting clouds ('popup clouds'), just tens of km across, on the STropZ and the whitened STB and STZ. Much information on cloud textures is contained in the images and maps.

Here I just summarise the views of the major features, as in our posted perijove reports. The best overall maps of them are copied in Figures 4 and 5.

(i) STB from PJ1 to PJ6: (adapted from Ref.7, esp. Figure A5):

All the images show similar patterns of cloud textures in different latitudes. The STropZ has a smooth, slightly streaky texture, whether all white (PJ3) or largely grey (PJ4) or mixed (PJ5, PJ6). The STBn jet has an elaborate wavy texture. The white STB has a very fine-grained texture of complex white clouds. The STBs jet can be discerned by irregular small streaks; and the STZ has a cloud texture intermediate between that of the STropZ and STB. (The PJ1 image, immediately following the STB Ghost, showed complex texture in the STB, but this image (a low-quality compression test) did not show whether it was different from undisturbed sectors at later perijoves.)

Some of the cloud textures may be three-dimensional; and on top of them are innumerable tiny white clouds that cast shadows, scattered most densely across the STB and STZ, which have been seen with increasing clarity at all perijoves from PJ3 (weakly) to PJ6 (best) (Figure A6 & PJ6 report).

In contrast to the fine-textured white clouds, larger spots (detectable from Earth) are generally diffuse, whether pale orange patches on the STBn jet (PJ4), retrograding dark spots in the STZ following oval BA (PJ3), or grey streaks in the STropZ (PJ4, PJ5).

PJ5 (2017 March 27):

The **STB Spectre** was the first major STB feature to be imaged [Figure 5]. It showed an impressive cyclonic circulation pattern, and evidence for an anticyclonic recirculation loop on its south edge.

(ii) STB from PJ7 to PJ16:

PJ8 (2017 Sep.1):

The highlight of PJ8 was the complete hi-res imaging of the **STB Ghost**. Beautiful circulation patterns are seen in and around the STB Ghost [**Figure 6**], as around the (smaller) STB Spectre at PJ5.

The structure is also the same as that of the (much larger) STB Fade during the Voyager flybys in 1979 (Figure 12), particularly the two-tone braided border. Although that formed in a completely different way, all these structures had matured into closed cyclonic circulations with the same appearance.

For the Ghost, a preliminary animation covering over a span of 8.0 minutes is posted as Figure S2. The circulation and the adjacent jets are perceptible. The most striking motions appear to be south of the f.(W) half of the Ghost, where winds diverge rapidly along the oblique boundary between the prograde S2 (SSTBn) jet and the retrograde circulation which curves north around the f. end of the Ghost.

South-following (Sf.) this boundary is the putative recirculation loop (Figure 6 & 11 & S2) [Figures 4 & 6]: here, the STZ is strikingly orange, with a well-formed grey anticyclonic vortex which appears to be the point of recirculation (probably identical to a dark feature that was was fixed at the f. end of the Ghost in the JUPOS chart then).

PJ10 (2017 Dec.16):

These images again give a superb sequence of views of the **STB Ghost**. This time they cover mainly the f. (west) half, and the recirculation loop. See hi-res maps in Figure S2, blinked in the attached animation. Better than PJ8, it clearly confirms the circulation of the Ghost, and especially the strong shear between the prograding SSTBn jet and the retrograding current into the putative recirculation loop.

PJ11 (2018 Feb.7):

The STB (p. oval BA, which is just visible coming over the limb) is entirely white, but contains one little vortex which I suggested might develop into the next STB structured segment. [However it was not recognised again.]

PJ12 (2018 April 1):

Juno flew **just p. the GRS, as the STropD was streaming round it**, and had a dramatic view of the turbulence in the STropZ and STB latitudes.

PJ13 (2018 May 24):

Images revealed the **STB Spectre** (Figures 3 & 8), that had recently been impacted and temporarily obscured (in ground-based images) by the turbulence emanating from the STropD. The images confirm that it is still intact; and will enable animation and measurement of the winds. [Figure 5].

PJ14 (2018 July 16):

The closeup images covered the sector of ***southern STropZ*** that was disturbed after the p-STropD passed the GRS; at PJ12, massive turbulence that was seen pouring into these latitudes. At PJ13, there was a very dark grey band in this sector; now this is pale orange, and does not show any turbulence.

The ***S. Temperate domain*** here was also massively disturbed at PJ12, and this was evident at PJ13 as many tiny dark spots (probably vortices). At PJ14, only one or two of these remain visible; but these latitudes do still look very turbulent at high resolution. This seems to have been an example of turbulence evolving from large to small scales.

PJ15 (2018 Sep.7):
Another excellent set of views of the ***STB Spectre*** (Figure 10), following its involvement with the STropD. It is much longer than it was at PJ5 and PJ13, but just as well-defined, and these images will enable animation and wind speed measurements. Vortices to its south suggest that a recirculation loop is re-forming there. [Figure 5]

PJ16 (2018 Oct.29):
Hi-res map of the sector f. oval BA, where the STB Ghost had transformed into a dark turbulent segment of STB [Figure 4]. As usual, this had emitted dark spots Sf. forming an expanding 'Sf. tail', replacing the recirculation loop; now the whole sector is more disrupted. The PJ16 images show this activity close up, including a small AWO, and several small dark grey spots. It is interesting that they are round and dark but show little sign of vorticity, and that they lie within a very bland cloud deck that covers this part of the STZ. Perhaps this cloud deck enables the dark spots to drift across the retrograde jet without being influenced by it?

PJ17 (2018 Dec.21):
The first good images of ***oval BA*** – now almost white. In the sector p. it, the domain is still largely blank with only small vortices. Animation of maps of BA allowed us to measure wind speeds.

3. Ground-based results

Figure 7 shows a set of maps from our posted reports, in L3. **Figure 8** shows the JUPOS charts for the domain for the three apparitions, in L2. Single charts covering 2014-2018, both in L2 and in L3, are presented in **Appendix B**, though they are less annotated than those in Figure 8.

3.1. Oval BA

Oval BA is the only large anticyclonic oval in the domain. It passed the GRS on 2016 Nov.1, and again during solar conjunction in 2018 Dec. Its size has not changed significantly during these years, up to 2018 Feb, as shown in **Figure 9A**. The outer dimension is for the white oval, and averaged 7.8 (±0.7) deg. The inner diameter is for the orange annulus, and averaged 6.2 (±0.25) deg.

The oval has distinct orange colour in a broad annulus with a white core. The colour varies. It was moderately red throughout the 2014/15 apparition, then during the 2015/16 apparition, it gradually became redder until by 2016 June it was as strongly red as it has ever been. The orange colour remained strong at least until summer 2017, and was still quite strong up to 2018 Jan., but it faded gradually during 2018. By October most colour had been lost [images in report no.9], and it was white in 2019 Jan. Even the JunoCam images in 2018 Dec. (PJ17) showed only a weak reddish tint in the annulus.

Oval BA sometimes has a dark grey rim or collar, and its story during these years confirmed our previous inference that this depends entirely on turbulent activity in the dark spot or segment f. the oval (see below). As this dark spot calmed down, oval BA lost its dark rim temporarily in 2016 Jan. and more definitely and completely in April; in early 2017 it had only a faint grey rim. But the dark spot on its f. edge still showed intermittent turbulent activity, which explains why in 2017 April-May, oval BA had a grey rim again. This activity ceased in mid-May, after which there was no grey rim. After the collision and transformation of the STB Ghost in 2018 Feb., a very dark grey collar developed as expected, and persisted throughout 2018.

3.2. Dark spots and dynamics of the Oval BA region

In our previous long-term reports [refs.2&3], we documented three events in which a STB structured segment (whether white or dark) collided with the dark spot on the f. edge of oval BA (Figure 2). In each case this results in a dark STB segment with small-scale turbulence; dark material emanating from it formed a dark rim around oval BA, and outbreaks of small dark spots or streaks both prograding on the STBn jet p. BA ('STBn jet outbreak'), and slow-moving or retrograding in the STBs jet and STZ f. BA ('South-following [Sf.] tail'). Oval BA accelerates (to DL2 = -14.2 to -16.5 deg/mth), but the f. end of the STB dark segment continues to prograde towards BA faster (DL2 = -15.4 to -17.8 deg/mth). When this segment has shrunk to a small dark spot, it becomes quiescent, and oval BA decelerates again (to -10.4 to -11.8 deg/mth), and the outbreaks of dark spots and streaks cease. We concluded that this is a reproducible cyclic phenomenon, and indeed it has been repeated in 2015-2018 in much the same way as before.

The latest of these collisions had occurred in 2013, and in 2014 the dark, micro-turbulent STB segment f. BA was contracting. I expected that it would shrink to become a quiescent dark spot in summer 2015, and oval BA would decelerate [ref.5]. In fact, this process was much prolonged, apparently because the dark spot, although small, showed continuing turbulence intermittently until 2016 Feb., and even thereafter on an even smaller scale. Thus the correlation between visible disturbance and the speed of oval BA was maintained, over a timescale of months, although as before, we do not see any shorter-term correlation.

Drift rate of oval BA (Figures 2 & 10 & Table 1):

As the quiescence of the dark spot was delayed, oval BA showed only partial and variable deceleration, from its mean speed DL2 = -14.1 deg/mth in 2014, via a marked fluctuation after it passed the GRS, to a mean of DL2 = -12.7 deg/month from 2015 June to Dec. It then underwent its major deceleration over a few months around the start of 2016, around the time that the dark spot f. it was quietening down. Then it had a slow but fluctuating speed for over 2 years until 2018 May-June, when it accelerated a few months after the creation of the next turbulent dark segment f. it. In the intervening years its speed fluctuated on various timescales: most distinctly with a period of approx. 2 months, but also more irregularly, perhaps with a period of about a year. It had mean DL2 = -10.9 (±0.3) deg/mth from 2016 Jan. to June, but then -12.0 from 2016 June to 2018 May. For most or all of this time it was oscillating between DL2 ~ -13.4 and -9.5 deg/mth with period ~2 months. The mean period was 65 days but it varied between ~50-90 days so it is not as regular as the GRS.   Similar oscillations were also occurring in 2015 and 2016, with periods in the same range, but were less obvious because of more longer-term variability in the drift rate then.

The latitude of the oval, in earlier years, had varied with its drift rate, but this was no longer evident: from 2015 Jan. to 2018 Sep. the mean latitude was always between 33.0 and 33.2ºS (except for one value of 32.6ºS), and not correlated with speed. (These values were averages over intervals of 1 to 4 months, at different drift rates ranging from -13.4 to -9.0 deg/mth, calculated by G. Adamoli from the JUPOS data.) Nevertheless, this constancy is not significantly inconsistent with our previous zonal drift profiles of BA [Ref.3 Fig.5], which were gradually shifting south towards the general ZWP until 2012. The narrow range from 2015-2018, in both latitude and speed, lies only ~0.1º south of the zonal drift profile from 2012-2014.

The dark spot f. BA:

In the 2014/15 apparition [ref..3 Appendix 1], the STB segment f. BA was gradually shrinking, but remained dark and, in v-hi-res images, micro-turbulent, up to 2015 May. In 2015 May it became a compact dark ring only 7º long; but the ongoing STBn jet outbreak p. BA suggested that the turbulence had still not ceased.

By 2016 Feb. [ref.8], the dark streak on the f. edge of oval BA had shrunk to a very small spot, ≤5º long. Actually, in Feb. the dark spot was still disturbed, and still emitting a few dark spots Sf. it and some dark material around oval BA and on STB(N) p. it; but these were faint or minor. In March it quietened down further. V-hi-res images still sometimes showed it disturbed and emitting spots Sf. it, but this was all at a very low level.

In 2016/17 (according to our interim reports), up to 2016 Dec., there was just a small dark spot f. oval BA which has been quiet since last summer. Thereafter, the dark spot enlarged again, and minor streaks and faint shading developed Sf. it. Up to 2017 May it was still moderately active , and generating a grey (not very dark) collar around BA, as well as retrograding dark spots in the Sf. tail.

The 'south-following tail' (Sf. tail):

In the 2014/15 apparition, this string of very dark streaks was initially ~70º long, but shortening. It was described in detail in the full report [ref.3 Appendix 1]. There were still some dark spots in the Sf. tail up to 2015 May, though becoming sparser.

In 2015/16 [ref.8]**,** the dark spots in the Sf. tail, produced up to 2016 March, were strongly retrograding, with DL2 = +11 to +36, at 31.3 to 32.5 ºS. These speeds were more positive than usual, matching the jet peak observed by spacecraft. The retrograding spots all decelerated suddenly and drifted south when ~20-30º f. the dark patch, mostly merging with others, and the mergers coalesced into a distinct ring in March (L2 30 --> 25). This was a typical origin of a small anticyclonic oval, although it is not clear whether this one survived after mid-May. There was also a rimless white spot f. it in March-May, which may have been tracked (via the JunoCam PJ1 map on 2016 Aug.27) into 2017 (Figure 8), then decayed during the transformation of the STB Ghost (Figure 3).

From 2017 Feb. to June [ref.9]**,** the dark spot was again emitting retrograding dark spots (DL2 ~ +21 deg/mth up to early May) [The JUPOS chart shows that one of them decelerated and oscillated between DL2 = +5 and -14 deg/mth, at the f. end of the Sf. tail. Around April 1 this came into contact with the small rimless AWO, at the p. end of the STB Ghost, which had just moved S there and accelerated towards BA.] In April-May there were many of them; but this activity ceased in mid-May, so the retrograding spots disappeared in June-July and BA then had no grey rim.

The collision and transformation of the STB Ghost, in 2018 Feb., had the usual dramatic effects, as described below.

3.3. The STB Ghost (STB structured segment E) and its collision with oval BA

The early life of the STB Ghost was described in our last long-term report [ref.3]:

[from Ref.3]:

The new STB structured segment E ('STB Ghost').

Structured segment E arose in 2011, as a small cyclonic dark spot called DS4, and it developed into a pale, expanding feature which we call the 'STB Ghost'. In its origin, appearance, and behaviour, it is an exact replica of the 'STB Remnant' of 2004-2009. The origin as DS4 was described in our 2011/12 final report (see Section 5(ii) below), and was summarised in our long-term report [ref.2], thus:

(E) Meanwhile another small v.d.s. (named DS4) appeared in 2011, in a small cyclonic faint blue patch, where there was also temporary disturbance of the SSTBn jet [ref.10]. It became remarkably dark in

2011 Nov., until 2012 Sep. Then it faded and turned white, within a faint cyclonic streak, just like other v.d.ss. have done, and we have predicted that it will become the next STB structured sector. (If it remains faint like the STB Remnant, we will suggest naming it the 'STB Ghost'.)

V-hi-res images showed turbulence around it in 2011 Nov. (Fig.1).

DS4 gradually faded from 2012 Aug. to Oct., and by late Nov. it had turned into a tiny, light pink spot, which was white in early 2013 [Ref.2, & 2012/13 report no.9]. All this time it was embedded in a faint grey or blue-grey oblique streak. Its structure has been unchanged from 2013 to 2015 [Figs.2-4, & 2013/14 report no.4, & **Appendix 1** below]: the faint blue-grey streak extends from a darker grey triangle at its Np. end on STBn, to a variable Sf. end in the STZ, and it appears to be a loop surrounding a white core – probably a cyclonic circulation. In methane-band images, it is conspicuously methane-dark. It passed the GRS in 2013 Nov-Dec.

Although it is essentially cyclonic, it induces anticyclonic circulation on its south edge, in that SSTBn jet spots are unable to pass it, occasionally recirculating into the STZ (see below).

Hubble and JunoCam images proved that it was a cyclonic circulation [see above: Figures 3-5]. Its structure remained unchanged from 2013 to 2018 Jan.: a pale blue loop with white interior, but methane-dark [ref.8, Figs.16 &17]. On its south edge, spots from the SSTBn jet sometimes recirculated anticyclonically [Section 3.5(ii) below].

Like other such segments [refs.2&3], it gradually grew longer. Measurements in **Figure 9B** show that, apart from a few fluctuations, its internal dimension grew at an average of 0.35 deg/month, from 7º long in 2014 to 19º long in 2017; and it outer dimension, though less well defined, grew at about the same rate.

Its drift rate is listed in **Table 1** (for the spot at the Sp. end): it averaged DL2 = -16.4 deg/mth. The f. end, therefore, averaged DL2 = -16.0 deg/mth.

In early 2018, the Ghost was converging on oval BA, and on Feb.4, the expected transformation began suddenly. The process is described in the following excerpts from our interim reports (with references to the original figure numbers).

2018 Report no.1 (2018 Jan.19) : III. Prospects for 2018:

The STB Ghost will soon collide with the dark spot f. BA; on present courses this would happen in late April, but interaction could begin at any time in the next six months. Spectacular effects could occur suddenly, as happened on 2010 June 17 when an identical feature, the STB Remnant, underwent an identical collision. Whatever the short-term events, I expect the overall effect to be as in previous such events, esp. in 2010 [ref.2; for details see: 2010/11 Reports no.4 & no.8, http://www.britastro.org/jupiter/2010reports.htm]. The STB Ghost will convert into a dark turbulent STB sector f. oval BA, oval BA will accelerate, and dark spots will be emitted p. on the STBn jet and f. in the STZ.

2018 Report no.2 (2018 March 12):

The STB Ghost, approaching oval BA, is undergoing a dramatic transition to a turbulent dark STB segment, as expected. This started on Feb.4 with a sudden convective outbreak in the form of a tiny brilliant spot – exceptional for this latitude, but just what was observed on 2010 June 17 in the same circumstances. Its development is shown in Figure 7 (set of maps), Appendix 1 (large set of images), & Figure 8 (**animation** showing its turbulence). A large set of maps has been posted by S. Mizumoto on the ALPO-Japan web site at: http://alpo-j.asahikawa-med.ac.jp/kk18/j180226t.htm.

The initial white spot was first imaged on Feb.4 by 4 observers in S. America, but was reported by A. Wesley on the next rotation when it was extremely bright in near-IR (continuum) and the methane band – though in RGB images it was only modestly bright for the next 2 days. It was rapidly stretched and twisted by the cyclonic circulation of the STB Ghost, as shown in the maps (Figure 7). Up to Feb.8, the white streak was still methane-bright while the rest of the Ghost remained methane-dark. Soon it filled the whole Ghost with turbulence, including some bright white and some very dark blue-grey spots, all changing very rapidly and evolving to smaller scales. It was still variegated in hi-res methane images (e.g. Feb.18) but gradually reverting to methane-dark. Now the turbulence has affected the adjacent dark spot f. BA, which appears disrupted or obscured as a brownish blur.

Additional note: The images from Feb.15-18, projected into maps by Michel Jacquesson, produced a dramatic animation [refd. as Fig.8 above] and measurements of the wind speeds. During the similar transformation of the STB Remnant in 2010, we recorded some of the fastest speeds ever seen in these latitudes, and we find similar speeds on this occasion: ***see Appendix A.*** Along the north side (27.9—29.3ºS), we find speeds of DL3 = -1.7 to -4.3 deg/day (u_3 = 22 to 55.5 m/s). Along the south side (32.8—33.6ºS), we find speeds of DL3 = +2.0 to +4.3 deg/day (u_3 = -24 to -52.6 m/s).

The transformation of the STB Ghost had begun on Feb.4 as it was only just starting to contact the small dark spot, and the emission of new dark spots p. and f. it did not start until the end of March, around the time that the two cyclonic features became indistinguishable. This process was excellently captured in two Hubble maps, made on 2018 April 1 and 17 [**Figure 3**]. The merger of the two cyclonic features occurred between the maps, and the former small AWO between them had become a grey patch, still with some vortical structure.

2018 Report no.3 (2018 May 7):

The segment of STB f. BA, created by the turbulent transformation of the STB Ghost in Feb., persists, and has generated an even darker sector of the STZ f. it, representing the 'Sf. tail'. Embedded in the 'tail' is a small AWO which has sometimes appeared reddish and methane-bright (Figure 4). The JUPOS chart shows that several dark spots have retrograded further f. this, with DL2 ~ +19 deg/month.

Oval BA now has a dark rim around it, and dark material prograding on the STB(N) Np. it, as expected. However it has not yet clearly changed its motion, which remains consistent with its previous 2-month oscillation.

2018 Report no.6 (2018 August 30):

The segment of STB f. BA, created by the turbulent transformation of the STB Ghost in Feb., is still dark and disturbed (Figure 11). After the transformation of the Ghost f. BA, the drift of its f. end has varied and is now about the same as BA's, so it is not shortening. The sector of STZ f. it ('the Sf. tail') has been extremely dark grey since April. There is still a tiny AWO embedded in it. The origin of the dark Sf. tail and of the embedded AWO (which was then reddish and methane-bright) is shown in Figures 11 & 12.

All the predicted effects of the STB Ghost collision have now occurred: its dramatic transformation into a turbulent dark STB segment; emission of dark spots p. it on the STBn jet and f. it in the STZ; a dark rim around oval BA; and acceleration of oval BA, which occurred decisively in May.

These reports and charts do not show the full extent of the acceleration, which became evident in the next apparition, Over solar conjunction, from 2018 Oct. to 2019 Jan., oval BA had DL2 = -15.5 deg/mth.

3.4. The STB Spectre (STB structured segment F)

The STB Spectre developed as a cyclonic dark spot tens of degrees p. BA in 2014/15, just as the STB Ghost had done. This was described in [ref.3 inc. Appendix]:

A new dark spot arose here in 2014 Dec., presumably cyclonic, developing into a very dark spot within an oblique cyclonic blue loop ~35º p. BA from 2015 Feb. onwards which we called DS5 (Fig.2 & Appendix). As previously suggested, it developed exactly like the STB Remnant in 2004 and STB Ghost in 2012, so it was named the STB Spectre.

It was still a very dark spot up to mid-Dec., 2015, but then became red-brown, which indicated that it was about to fade away. Indeed it faded rapidly in 2016 Feb. [ref.8]. By May, DS5 had brightened to light pink – still within its pale blue shroud -- and was passing the GRS; then the spot became white as expected. The blue loop around it persisted and was methane-dark (though not yet as dark as the STB Ghost). Its speed from 2016 Jan. to mid-May was typical: DL2 = -16.4 (±0.3) deg/mth. By 2016 May, its drift rate was -15.5 deg/mth, and the Spectre was ~3.5° long internally, and ~10-11° long externally.

Measurements of its length in 2016 and 2017 (**Figure 9B)** suggested a growth rate similar to that of the STB Ghost.

On 2017 Oct.24, the planet was fully mapped by JunoCam at PJ9 during solar conjunction, unexpectedly revealing a new South Tropical Disturbance (STropD), i.e. a recirculation across the S. Tropical Zone. Amateur images and JUPOS analysis showed that it was initiated in early August when dark streaks, modestly retrograding in the northern STropZ, merged and recirculated into the mid-STropZ alongside the p. end of the STB Spectre. *[Images and charts were collated but are still to be be shown in a forthcoming final report on 2016/17; the JUPOS chart for the origin of the STropD was posted in 2018 Report no.2, with maps from PJ9 onwards.]* It seems likely that the Spectre's circulation catalysed this rearrangement in the adjacent zone. By 2018 Jan. the Spectre, maintaining its usual drift, had moved ahead of the STropD, and was passing the GRS and very inconspicuous.

In 2018 Feb. *[2018 Report no.2 (2018 March 12)]* the Spectre became patchily shaded, being involved with the turbulence from the STropD (see Section 3.5(iii) below), and its outline was indistinct; but it was still well defined in methane images, from Juno at PJ11 (Feb.7), and from amateurs subsequently (Figures 3 & 6, & Appendix 1). In early March it was lighter again internally.

JunoCam images from PJ12 to PJ15 [Section 2.2] documented the S. Temperate sector f. the Spectre, affected by the turbulence from the STropD, which evolved to smaller scales until it was negligible. Excellent images of the Spectre itself at PJ13 (May 24) and PJ15 (Sep.7) (**Figure 5**) showed that it was still an intact circulation, much longer than before, and again with what appears to be a recirculation loop south of it.

Structured segments such as the STB Ghost and Spectre usually retain steady drifts, but this is not the case now. The STB Spectre accelerated and lengthened as it passed the GRS in Dec-Jan. (perhaps influenced by turbulence already streaming past it from the STropD on the STB(N), but before it was directly impacted by further turbulence from the STropD in March). Drift rates from the JUPOS charts are given in Table 1, and from 2018 April to July the STB Spectre had DL2 = -21.6 (±0.6) (p. end) and -20.4 (±1.3) (f. end). So as of 2018 July, the Spectre was converging on the dark STB segment at up to 8 deg/mth – but they may yet revert to more typical speeds.

3.5. Recirculation and eddying in the STZ

In our previous long-term reports [refs.2&3] we described two types of anticyclonic recirculation that are repeatedly observed across the STZ:
(i) Recirculation southwards from STBs to SSTBn, p. oval BA.
(ii) Recirculation northwards from SSTBn to STZ/STBs, at the STB Remnant or Ghost.
Both of these have been observed subsequently: occasionally (i), and routinely (ii).

(i) Recirculation southwards from STBs to SSTBn, p. oval BA.

Edited from [ref.3]:
A dynamical feature appears to have developed tens of degrees p. oval BA, which is inconspicuous and not yet understood, but appears to be persistent (Fig.2). First, SSTBn jet spots have repeatedly arisen at this location ~60-80° p. oval BA, in 2006, 2007, and 2011/12. Also, cyclonic dark spots in STB have arisen here, and recirculation from STBs to SSTBn has been observed twice. In **2011/12** [ref.10], all three phenomena occurred, including the origin of cyclonic dark spot DS4 which became the **STB Ghost**.

Exactly the same happened in **2014/15**. A new dark spot arose here in 2014 Dec., presumably cyclonic, developing into a very dark spot ~35° p. BA from 2015 Feb. onwards which we call DS5 (Fig.2 &

Appendix 1) [quoted above as the origin of the STB Spectre]. In 2015 April, a tiny dark spot on the STBs jet retrograded past DS5 to ~25º p. BA where it recirculated to prograde on the SSTBn for few days; a similar spot had followed part of the same course in March (see **Appendix 1**). From here to BA, the STZ and STB latitudes were somewhat darkened, consistent with a circulation across the STZ ~25º p. BA [Figure 1].

No other recirculations were mentioned in our interim reports for 2012-2014. However, this sector p. BA was just where the STBs jet was found to be weaker in ZWPs obtained in early 2014 [G. Hahn ref.] – consistent with a tendency to recirculation here, & with the fine texture of the STZ in the HST images. This seems to be a recent development, as there was no such recirculation in 2000 in the Cassini movie.

Similar recirculation was observed in 2016 Jan. [Ref.8]: As dark spot DS5 faded to become the STB Spectre, two small dark spots arose Sf. DS5 and retrograded (DL2 = +24, lat.33.2ºS); around Jan.23 they halted, 20-30º p. BA, then began prograding in STZ (one reaching DL2 = -24.5, lat.34.3ºS). Meanwhile a third spot emerged Sf. DS5 and retrograded like the first. They all paralleled the ZWP though 0.5º south of the Cassini profile – perhaps suggesting an altered ZWP in this region. The origin of the spots was unclear but they could have been induced by a new large turbulent sector (FFR) in the SSTB which developed alongside this sector in Jan., with disturbance moving north from there alongside DS5 to the STBn jet.

This was the last time we observed recirculation p. oval BA. In Juno images we see no circulating pattern there, so no permanent structure has been established. But transient spots have still appeared in this region. In 2018 [Report no.6], the following dark spots all appeared tens of degrees p. oval BA; they could be further consequences of the transformation of the STB Ghost.
(1) A pair of dark spots in the SSTBn jet (the only spots recorded in it in 2018), tracked from late March until mid-May.
(2) A dark spot in southern STZ (34ºS) which appeared in late May (33 --> 40º p. BA; DL2 ~ -19 deg/mth), followed by a dark streak alongside the SSTBn from mid-June to early July (DL2 ~ -23).

(ii) Recirculation northwards from SSTBn to STZ/STBs, at the STB Remnant/Ghost/Spectre

Recirculation in this sense, anticyclonically from the prograding SSTBn (S2) jet into a slow flow in STZ or retrograding flow on the STBs jet, was recorded repeatedly at the f. edge of the STB Remnant [ref.2] and at the STB Ghost (2013/14, 2014/15). These events, including one in 2015 April-May, were described in [ref.3 inc. Appendix]. Below are edited versions of our posted accounts of subsequent developments.

Adapted from our final report for 2015/16 [ref.8]:
In 2016, we observed more frequent recirculations than ever before, and evidence for an altered ZWP f. the STB Spectre.

The SSTBn (S2) prograde jet carried an unusually large number of small dark spots.... None of them got past the STB Ghost. The first spot to reach the Ghost, in Jan., halted and then probably disappeared. Then in April-May a volley of five spots arrived in succession; all of them recirculated to retrograde (temporarily) in the STZ f. the Ghost [JUPOS chart & Fig.17]. The recirculations occurred rapidly; when each SSTBn jet spot reached the mid-point of the Ghost, it shifted north and started retrograding past the f. end of the Ghost. Three survived, but all reversed their drift again when 10-20º from the f. end of the Ghost, and adopted a prograding drift typical of the STC (DL2 = -20 or -12 deg/mth). Throughout, all these spots changed their latitude along with their drift rate, adhering to the Cassini ZWP [Fig.20].

Similar recirculations occurred at the STB Spectre. We already described [see above] how several new retrograding spots appeared at DS5 in Jan. (DL2 = +24 to +26.6), which then merged to make two spots, which reversed their drifts to prograde ~20-30º f. DS5, with typical STC drifts ranging from -4 to -19 deg/mth. Meanwhile, three SSTBn jet spots appeared in the same sector and prograded to the Spectre, where one halted (early April) and the other two recirculated: (DL2 = -82 --> +35, and -56 --> +29; Fig.21.)

The retrograding speeds between the Spectre and BA were exceptionally high – as was also observed between the Ghost and BA in 2014/15 [ref. 19]. These points were also anomalously far south, ~1.0º south of the nominal jet peak; indeed, the whole ZDP for the SSTBn jet and STZ in this sector was displaced southwards [Fig.20]. We observed the same anomaly for recirculated spots f. the STB Remnant in 2004-2007 [ref.18]. This is the sector in which we are now recording recirculation at both ends, so it is possible that it has an anomalous ZWP and will speed up.

Combining the data on all retrograding spots in the STZ in all three sectors, we recorded substantial speeds for 15 dark spots, with mean DL2 = +24.6 (±6.4); range +10.7 to +35.9 deg/mth. These are typical of the full STBs jet speed recorded by spacecraft (+20 to +42 deg/mth)., and are more positive than usually observed, except for the Sf. tail of the dark segment f. oval BA in 2005-2007. The speeds observed f. BA in this apparition represent a return to that speed range.

These events confirm that the STB Ghost and Spectre, like the earlier Remnant, block the passage of all SSTBn jet spots, and cause most of them to recirculate. Indeed we recorded more such recirculations in this apparition than in any previous one. But it is notable that all the recirculated spots, f. the STB Ghost and Spectre, retrograded for only a few tens of degrees before they either disappeared or reversed their drift again to join the STC. (This was also typical for spots recirculated from the STB Remnant and Ghost in earlier years [refs.2&3].) The retrograding spots in the 'Sf. tail' f. oval BA behaved in exactly the same way, although they were generated from the STB dark patch instead of from recirculation, but these spots have retrograded much further in some previous years [refs. 2&3]. Possibly this drift reversal occurs when the spots evolve into more substantial vortices, which then adopt a more stable position in the STZ.

Adapted from our 2016/17 Report no.10 (2017 May) [ref.9]:
Once again we found that prograding spots from the S2 (SSTBn) jet are halting or recirculating south of the Spectre, as shown in Figure 9. In fact, these spots seem to be travelling around an elongated ‘recirculation loop’ – which can be seen as a pale grey line around an orange oblong in some v-hi-res images, esp. by Olivetti. It is ~20-27º long with its p. end due south of the Spectre. The JunoCam closeup images of the Spectre at PJ5 on March 27 actually covered the p. end of this recirculation loop (Fig.9). The loop can also explain observations from last apparition *[see final paragraph above]*. It remains to be seen whether this loop is now a permanent structure, or will gradually become one. If so, it could be the start of the next generation of great white ovals in the S. Temperate domain.

Adapted from our 2016/17 Report no.14 (2017 August) [ref.9]:
In summer 2017, many SSTBn jet spots were impinging on the STB Ghost and halting or recirculating there, as they were earlier at the STB Spectre.

Adapted from our 2018 Report no.1, reproduced from our Juno PJ9 report:
At the end of 2017, there were various signs of possible disturbance in the S. Temperate domain, and it seemed potentially ripe for a revival of the now-absent STB, as last happened in 1993 [ref.21]. In the PJ9 map (2017 Oct.24) we can see:
--disturbance apparently prograding on the STBn jet from the new STropD towards the GRS;
--various small dark spots in the domain p. the GRS;
--the STB Ghost is still pale, but there is the (short) orange recirculation loop Sf. it; and it is approaching the dark spot f. oval BA, so I expect a vigorous interaction when they collide in 2018 [as occurred; Section 3.3. above];
--the orange recirculation loop Sf. the STB Spectre now appears to be ~50 deg long.

(iii) Effects of the S. Tropical Disturbance (STropD) in 2018

The origin of the STropD in late 2017 was summarised above (Section 3.4). Its progress was described in our report on PJ9 and our interim reports for 2018 (esp. nos.2, 3 & 6, which contain many illustrations). This was the first opportunity in the modern era to study a STropD interacting with a previously undisturbed SEB and with the GRS. One revelation was how turbulent it all was: it was a ‘disturbance’ not just in the formal sense of a reconfiguration of the jets, but in the colloquial sense of intense turbulence and convection. This was evident within the SEB, and within the dark p. end itself; and on the S.Trop.Band as it streamed past the GRS. Its effects in the S. Temperate domain are summarised here.

Its p. end (p-STropD) arrived at the f. edge of the Red Spot Hollow on 2018 Feb.4, and turbulent material from it promptly began streaming around the S side of the GRS and accumulating turbulence in the S. Temperate domain and S. half of the STropZ on the p. side of the GRS. An **animation** showing this activity was posted with our 2018 report no.3, and Juno imaged it closely at PJ12. Spots p. the GRS could not be tracked for long; a few speeds are given below (Section 3.6), and were slower than usual for their latitudes.

The evolution of this turbulent sector p. the GRS can be followed in the ground-based maps [Figure 7] & Juno STB Spectre maps [Figure 5]. The p-STropD never re-formed; as the turbulence waned, a narrow dark S. Tropical Band (STropB) at 25-26ºS became prominent. But soon after the f. end (f-STropD) arrived at the GRS on May 30, images from June 12 onwards showed that it did survive passage round the GRS, and terminated the dark STropB. But the whole sector then returned to normal: the turbulence had almost entirely subsided by PJ14 (July 16); the STropB here turned orange and faded in 2018 July-August; the new f-STropD became inconspicuous, although it persisted until August.

3.6. The STBn jet

In 2014/15 [ref.1, Appendix], a substantial outbreak of spots on the STBn jet that began in 2013 was continuing, though varying in intensity**.** Activity re-intensified during 2014 Dec. to produce a long, very dark STB(N) with jet spots in 2015 Jan. [ref.1, Appendix], and STBn jet spots were still appearing in 2015 May.

In the 2015/16 apparition [ref.8], the STB(N) was merely a very faint narrow band at all longitudes, apart from occasional, very minor streaks p. BA. Only three small spots were tracked on it, all starting at oval BA and disappearing when they reached the GRS. Speeds were DL2 = -77.4, -67.5, and -64 deg/mth.

In the 2016/17 apparition, the STB was completely absent, with no STB(N) nor STBn jet spots.

In 2017/18, when the STropD appeared in autumn 2017, a narrow dark 'South Tropical Band' (STropB) formed all around the planet, continuous with the p. and f. ends of the STropD [see maps from PJ9 and 2018 Jan-Feb. in Figure 7]. Being at 25-26ºN, this was too far north to be a normal STB(N). P. the GRS, in 2018 Feb.-April, it was further reinforced and broadened by the turbulence from the STropD [Section 3.5], as far as the STB Spectre, and then became a dark grey band; but this turned orange and faded in 2018 July-August.

Meanwhile, after the STB Ghost transformed into the turbulent STB segment f. BA, dark material began to stream along the STBn jet p. BA from late March onwards, forming a dark STB(N) which persisted [see maps in Figure 7, & in Fig.11 of Report no.6]. This was the predicted STBn jet outbreak. Disturbance on the STB(N) was dense but only a few distinct spots could be tracked, as follows [from Report no.6]:

(1) Small dark spots arising p. the GRS, from the STropD as it passed the GRS, in Feb-May. Of many spots seen, I found just five plausible tracks, with DL2 increasing from -40 (one in early April) to ~-47 (±1; three in April-May) to -56 (one in May-June). [Subsequent unpublished JUPOS analysis by G. Adamoli established only two well-defined tracks, with DL2 = -38 (24.9ºS, in March) and -83 (26.0ºS, in April); these drift rates were unusually slow for their latitudes.]

(2) Small dark spots arising from the edge of oval BA, embedded in the dark STB(N), tracked in May-July at latitudes 29 --> 28ºN; DL2 = -87 (±1) (n=3) and -74 (n=2).

So in June, STB(N) was a very narrow dark belt all around the planet, apparently darkened due to turbulence both from the STropD and from the region of oval BA. But in mid-August, the only remaining very dark STB(N) is the sector p. BA, as far as the GRS [Report no.6, Figures 1-3], which was also spotty with STBn jet spots.

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In Appendix A:

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FIGURES:

Figure 1. Diagram of the jets and circulations in the S. Temperate domain.
(A) South up, matching JUPOS charts (= Fig.2 of Ref.3); **(B)** North up, matching other maps in this report.

Figure 2. Summary JUPOS chart of oval BA & STB segments, 1998-2018.

Figure 3. Examples of maps from Hubble images, posted by the OPAL project [ref.4 & https://archive.stsci.edu/prepds/opal/)], or the WFCJ project [ref.6 & https://archive.stsci.edu/prepds/wfcj/]. These show the STB Ghost and oval BA. The map on 2017 Feb.2 is one of two used to measure the Ghost's circulation (**Appendix A**). The maps on 2018 April 1 and 17 show the region soon after the Ghost had transformed into a turbulent dark segment of STB, and was emitting dark waves on the STBn jet and a dark 'South-following tail' in the STZ. At this time, it merged with the former dark spot (DS) f. BA, and a former AWO (probably the one shown in the 2017 Feb.2 map) was merely a dull grey vortex, but a new AWO (reddish at this time) had developed in the Sf. tail.

Figure 4. Excerpts from JunoCam maps (as posted in our perijove reports), showing the STB Ghost and oval BA, including the bright convective outbreak in 2018 Feb. that initiated the transformation of the Ghost into a dark STB segment.

Figure 5. Excerpts from JunoCam maps (as posted in our perijove reports), showing the STB Spectre.

Figure 6. Closeup JunoCam images of the STB Spectre at PJ8, with circulations indicated (from our perijove report).

Figure 7. Set of maps (labelled) from our reports, 2015-2018, in L3.

Figure 8. Triplet of full JUPOS charts for 3 apparitions, in L2 (& opposite orientation to the maps). (***Suppl.Figs in Appendix B:*** **Integrated JUPOS charts, 2015-2018, in L2 & L3.)**

Figure 9. Lengths of S. Temperate structures, in degrees longitude.
(A) Oval BA. The outer dimension is for the white oval, the inner diameter is for the orange annulus within it. In some measures the outer diameter appears reduced as the outer part was temporarily light grey (early 2017) or dark grey (2018). All measures are from Hubble or Juno maps except the large blue symbols which are apparition means from JUPOS (from G. Adamoli).
(B) The STB Ghost and Spectre. Measures are from maps produced by JUPOS, Hubble, and JunoCam. The outer dimension extends from the blue-grey triangle at the Np. end to dark spot(s) at the Sf. end; the latter are variable, often being features of the recirculation loop, so the outer dimension is ill-defined, though most readily measured in ground-based maps. The inner dimension is for the well-defined, slightly reddish internal loop, resolved in spacecraft images and the best ground-based images.

Figure 10. JUPOS chart of oval BA, 2014-2018. In 2016 and 2017 the ~2-month oscillation is indicated.

Table 1:

Mean drift rates of structured segments in S. Temperate domain	
(from JUPOS charts)	
	DL2 (deg/mth)
Oval BA	
2014 Feb-Nov.	-14,1
2015 June-Dec.	-12,7
2016 Jan-June	-10,9
2016 June--2018 May	-12,0*
*(oscillating between -13.4 and -9.5)	
STB Ghost (p. end)	
2014 Jan.--2015 May	-15,4
2015 June-Sep.(conj'n)	-17,8
2015 Oct.--2016 June	-16,5
2016 July-Dec.(conj'n)	-17,8
2017 Jan.--2018 Jan.	-16,1
2014 Jan.--2018 Jan.	-16,4
STB Spectre (p. end)	
2016 Apr.--2017 May	-15,4
2017 June-Dec.(conj'n)	-16,9
2017 Dec.--2018 July	-21,6

Appendix A: Wind speeds in the STB Ghost

A1. Winds in the quiescent STB Ghost (from Hubble maps)
--John Rogers (2019 Feb.)

The cyclonic circulation of the quiescent, light-coloured structured sectors – the STB Remnant, Ghost, and Spectre – has been observed in Hubble maps [ref.1], but not yet measured. I therefore made measurements of the Ghost from the Hubble maps of 2016 Feb.9 (OPAL project, ref.4 & https://archive.stsci.edu/prepds/opal/) and 2017 Feb.2 (WFCJ project, ref.6 & https://archive.stsci.edu/prepds/wfcj/#dataaccess.).

These are pairs of cylindrical maps in L3, in colour, taken on successive rotations of the planet. By 'blinking' the maps, the winds all over the planet are vividly visualised. For two reasons, they are not ideal for measurement: (i) The times of images used for each sector are not specified; (ii) There are distortions of the maps in some areas, made evident by blinking, which probably reflect imprecision in the map projections and alignments of the images, and possibly in one sector, an interval of two rotations rather than one. So measurement of longitude shifts between the maps, esp. at high latitudes, sometimes produces values that are inconsistent with ground-based speeds, or too scattered to be realistic. This was the case with the STB Ghost in the maps of 2016 Feb.9.

This report presents only results from 2017 Feb.2. (One map is in **Figure 3**.) I measured displacements in L3 between the two maps in two ways, as follows, and assumed an interval of 9.6 hours between them, which is typical for Hubble imaging.

(i) Visual alignment of whole latitude bands, representing the jets from SEBs to SSTBs.

A band was offset to east or west until it was best aligned with the same band on the other map. Results are listed in **Table 2**, and shown in red on **Figure A1.** 'Error bars' are the range of latitudes covered and the range of plausible average displacements (as there is always some relative motion of small features along the jet; some outliers were ignored). (Exception: the red point at 29.3ºS is the mean of the nearby green points.)

These sectoral averages agree very well with the Cassini ZWP for the jets on SEBs (f. the GRS), STBn (alongside the STB Ghost -- although it does not show the usual very fast sub-peak at 27ºS; is this suppressed here?), and STBs (dark spots p. the Ghost). The SSTBn and SSTBs jets are exceptionally fast; I think this is a cyclonic circulation like the STB Ghost.*

Rapid circulation around a blank sector of SSTB:

This analysis shows exceptionally fast speeds for the jets on SSTBn (a string of small dark spots) and SSTBs (tiny ripples running up and down along a visible wave pattern – the clearest example yet of a genuinely undulating jet). These are the edges of a long blank sector of SSTB with closed ends at AWOs, probably a circulation like the STB Fade. Likewise, in Hubble maps in 2014, we found exceptionally rapid speeds flanking a pale oblong in the NTB which we identified as a cyclonic cell [ref. below]. **So in all three domains, we find that a quiescent pale cyclonic sector of belt, with a sharply-bounded, light-coloured interior, has a circulation which is much faster than the equivalent jets in normal sectors.**

Hahn G & Rogers J (2015) 'Zonal wind profiles from ground-based and Hubble images, 2014 February and April.' http://www.britastro.org/jupiter/2013_14report10.htm

(ii) Tracking of individual points on the northern and southern sides of the STB Ghost.

Results are shown in green on **Figure A1.**

Table 2:

Drifts between Hubble OPAL maps, 2017 Feb.2								
VISUAL ALIGNMENT OF WHOLE LATITUDE BANDS:								
	Lat.		Shift		DL3		*u*	
	(deg.Sg)	(+/-)	(deg)	(+/-)	(deg/mth)	(+/-)	(m/s)	(+/-)
SEBs	20,7	0,2	1,66	0,08	124,5	6,0	-56,4	2,7
STBn/STropZ	26,0	0,8	-0,94	0,15	-70,5	11,3	30,8	4,9
STBn/STropZ	27,5	0,4	-1,16	0,2	-87,0	15,0	37,6	6,5
STB Ghost:								
--N edge (mean)	29,3	0,6	-1,80	0,30	-135	22,3	57,5	9,5
--N edge	30,0	0,2	-1,38	0,16	-103,5	12,0	43,8	5,1
--S edge	32,3	0,2	1,14	0,07	85,5	5,3	-35,4	2,2
STZ (p. Ghost)	32,5	0,3	0,48	0,1	36,0	7,5	-14,9	3,1
SSTBn	36,6	0,5	-1,74	0,13	-130,5	9,8	51,5	3,9
SSTBs	39,8	1,2	0,48	0,04	36,0	3,0	-13,7	1,1

The STB Ghost shows very high speeds on both N and S sides, by both methods. On the N side, the speed along the visible N edge (43.8 m/s, 30.0ºS, for the series of oblique streaks) is not the fastest: elusive faint features further N have faster speeds, albeit quite scattered, with an average of 57.5 m/s at 29.3ºS. On the S side, the well-defined oblique streaks on the visible S edge have the fastest speed, -35.4 m/s at 32.3ºS. (The wind speed gradient is 30.0 m/s/1000km.)

So the fastest speeds are at the usual latitudes of the STBn 29ºS sub-peak and the STBs jet peak, as tabulated in **Table 3**. They are much faster than recorded in ZWPs for undisturbed STB, and are in the same range as for turbulent dark segments of STB, so the quiescent STB Ghost is similar to those turbulent segments in its wind speeds. During its subsequent transformation (see below), its wind speeds did not change much except that some features on its S edge moved even faster (as also observed for the STB Remnant transformation in 2010).

A2. Winds in the STB Ghost during its transformation, 2018 Feb.

--John Rogers (2018 Oct.)

It was of great interest to measure motions in the STB Ghost during its transformation because during a previous instance of the same phenomenon – the transformation of the STB Remnant in 2010 – we recorded some of the fastest speeds ever seen in these latitudes. We have now found similar speeds on this occasion.

We used 6 hi-res amateur images in 2018 Feb.: 3 on 3 consecutive rotations on Feb.15-16, and 3 on 3 consecutive rotations on Feb.18. The images were projected as cylindrical maps by Michel Jacquesson using WinJupos. Longitudes are in System III (L3); latitudes are planetographic.

We also made an animation of the 6 maps. This shows that the chaotic appearance of the Ghost is very turbulent and rapidly changing. Its cyclonic circulation can be discerned between the 3 maps on Feb.15-16, although there are also many changes in the spots over those 20 hours; and also between the 3 maps on Feb.18, when the spots retain their identities better although there is still much variation. Spots can be seen moving rapidly along the north and south edges, and curving around the p. and f. ends, with churning internally. There are also indications of meridional wave motion on the south edge. I cannot trace distinct spots from Feb.16 to 18.

To determine wind speeds within the Ghost, I measured positions of all spots within it which could be confidently identified between consecutive maps, using the L3 scales on the maps.

Accuracy of measurements:
It was evident that there were some offsets between the maps in longitude and latitude, probably due to inaccuracy of the quoted image time and/or of the outline of the image. Therefore I also measured the positions of 6 white spots distributed around the outside of the Ghost whose drift rates in mid-Feb. were accurately known from the JUPOS project. (They were: two AWOs in the S2 domain; two small retrograding white spots in the SEB(S); a small AWO in the STZ just p. the Ghost; and the centre of oval BA.) Having plotted their measured positions from the 6 maps, I estimated the corrections needed to restore them to tracks with their known drift rates, and consequently applied a correction to the L3 values derived from 3 of the 6 maps (by +1.0º, -1.0º, and -0.4º). Accuracy of the resulting measurements.....[t.b.d.].

Here I include only the 13 drifts measured for spots near the north and south edges of the Ghost, omitting those near the p. and f. ends which could be seen to be slower and curving around the ends.
Four values have lower confidence because they were derived from just 2 maps on Feb.15-16, one of which had been corrected in L3. However, these values agree well with the others.
Conversely, 7 values were derived from all 3 maps on Feb.18, and so have highest confidence. In these 7 cases, the mean difference between DL3 values derived from the first and second maps versus the second and third maps was 0.60 deg/day, which gives an indication of the uncertainty of the measurements (although this figure may be inflated by real variations in speed).

Latitudes have been estimated from the scales provided. It would be possible to improve them by correcting for slight offsets which are evident between the maps.

Results:
Along the north side (27.9—29.3ºS), I find speeds of DL3 = -1.7 to -4.3 deg/day. All but one of these were in the range -1.7 to –2.9 deg/day, but one (consistent over 3 maps) had -4.3 deg/day.
Along the south side (32.8—33.6ºS), I find speeds of DL3 = +2.0 to +4.3 deg/day, including 3 spots above +4.0 deg/day. (There was also one large spot centred at 32ºS, i.e more internal, with a slower drift of +0.6 deg/day.)

When the speeds are plotted against latitude (**Figure A2**), they show a good gradient – surprisingly good, considering the evident turbulence in the Ghost and the unrefined latitude measurements. On the other hand, at the latitudes of the fastest measured speeds (28.0ºS and 32.9ºS, ±0.1º), a wide range of fast speeds are found which do not show a gradient.

Discussion:
Table 3 compares these speeds with those established for other structured segments in the same domain. The conclusions are as follows.

The STBn jet (northern sub-peak at 26-27ºS) is fairly constant along *all sectors* at 39 (±6) m/s [ref.2, confirmed by ref.6], except that it had an average of 57 m/s in the 1990s according to meas'ts from HST images [ref.11]; they had multiple consistent meas'ts so this appears to be a real variation.

The STBn jet (southern sub-peak at 28- 29ºS) is generally weak or absent in *undisturbed sectors*, but stronger in *dark turbulent sectors* with a mean peak of ~44 (±4) m/s [our long-term report, confirmed by others], but a considerable range within one such sector [ref.12]. Our meas'ts for the STB Remnant and Ghost when transforming into dark turbulent sectors are consistent with these values. Our mean speeds for the outermost spots agree well with them, and our fastest speed (55.5 m/s) is slightly exceeded by one of 62 m/s measured in 1997 [ref.12].

White circulating sectors of STB, such as the Remnant and Ghost before they transformed, had not been measured until now. The values reported above show that the quiescent STB Ghost is similar to turbulent dark STB segments in its wind speeds. (These values are similar to rough estimates that can be made for the Ghost from the Hubble maps in Tollefson et al.[ref.6], and for the Spectre from recent JunoCam maps [Gerald Eichstädt, personal communication].)

The STBs jet (retrograding) has rather low speed averaging -15.6 m/s in *undisturbed sectors*, but -35.4 m/s in the quiescent STB Ghost, and variable, usually faster speeds in *dark turbulent sectors* (-10 to -38 m/s) [ref.2, confirmed by ref.6]. Our measurements for the *STB Remnant and Ghost when transforming* into dark turbulent sectors, albeit for only a few spots, include even faster spots (-44.4, -52.6 m/s).

Figure A1: Chart of zonal speed vs latitude for the STB Ghost and nearby regions, compared with the Cassini ZWP.
Figure A2: Chart of zonal speed vs latitude for features in the STB Ghost during its transformation, 2018 Feb.15-18.

Table 3:

Jet speeds flanking the STB and its structured sectors

Tabulation by JHR in {Jup 2017-18 / STBO-BA.... / STB-Ghost_2018_JHR.xlsx} [Numbers in square brackets are SD or range]

SUMMARY		**STBn**				**STBs**		
	Year(s)		Lat.	DL2	u3	Lat.	DL2	u3
			('graphic, S)	(deg/mth)	(m/s)	('graphic)	(deg/mth)	(m/s)
STBn jet (N comp.), all sectors:								
Undisturbed sectors	2000-2012	N comp.	26,7	-93,8	37,4			
			[0,42]	[13]	[5,5]			
	2008-2016		26,5--27,0		33 to 43,5			
Alongside dark turbulent sectors		N comp.	25,7	-96,8	38,9			
			[0,74]	[30]	[13]			
	(2012 only)		26,2	-114	46,3			
			[0,2]	[3]	[1.3]			
	1995-1998	N. comp.	26,4	**-138,2**	**56,8**			
STB: Undisturbed sectors								
Means from ZWPs	2000-2012	S comp.	29,0	≤-80,4	≤31,0	31,9	29,5	-15,6
[from our long-term report 2000-2012]			(if present)	[26,2]	[<23 to 39]	[0,1]	[2,3]	[0.9]
STB: Dark turbulent sectors	2007; 2012	S comp.	28,7	-110,9	44,1	32,0	49,0	-23,7
[from our long-term report 2000-2012]			[0,06]	[3,0]	[1,2]	[0,20]	[+16 to +83,5]	[-10 to -38]
II. [GM&SL, 2001, Icarus 152, 316]	1997	S. comp.	~29		~41	~32,5		~-29
III. [MJ&SL, 2002, Icarus 160, 325]	1997	S. comp.	28		47	32		-22
					[30 to 62]			[-8 to -39]
IV. [Tollefson et al., 2017, Icarus 296, 163]	2009; 2012	S. comp.	29,0		36; 39,5			
STB Remnant tnsfm'n 2010	2010	N. edge	29	-110	43,5	33	100	-44,4
							[10]	[4]
STB Ghost tnsfm'n 2018	2018	Range	29,3	-59,6	22	33,0	51	-24,2
[this work]: Range along N and S edges:		along		[10]	[4]		[12]	[5]
		N/S	28,0	-95; -137	37,5; 55,5	33,0	120	-52,6
		edge		[10,5; 9]	[5,5; 4]		[3]	[1,2]
STB: white circulating sectors								
STB Ghost	2017	N. fringe	29,3	-143	57,5	32,3	77,5	-35,4
[this work]				[22]	[9,5]		[5,3]	[2,2]
		N. edge	30	-111,5	43,8			
				[12]	[5,1]			
Sectors with STBn jet outbreaks								
[Not included here. For details of these, & ZWP, see our long-term reports 2000-2012 and esp. 2012-2015]								