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Jupiter in 2015/16: Final report

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Summary

In the 2015/16 apparition, activity on the planet developed more-or-less in line with predictions we made a year earlier, albeit more slowly than expected. Thus a sector of the NEB expanded northwards (although this event then regressed); normal activity continued in the SEB (though with a brief pause); oval BA decelerated as adjacent turbulence declined; and a North Temperate Disturbance continued to dominate that domain. Both the NTB and STB were largely absent.

These major developments during the apparition have already been covered in our interim reports. This report adds tables of the locations and speeds of the major spots and the major currents. Otherwise, this report concentrates on fine details, which are still giving us new insights into the dynamics of the jovian atmosphere. For example, we report circulation patterns developing in the STZ, and waves moving along the SEBs and S4 jets. As usual, we detect both anticyclonic ovals and retrograding or slow-moving dark spots in most of the high-latitude domains, and prograding spots on the N2, S2 and S3 jets. **For a shorter summary of the apparition**, with more background information, we recommend **Report no.9** [ref.1].

Three Appendices present topics of special interest:
Appendix 1: **The SEBs jet in 2016: wave motions and super-fast motions.**
Appendix 2: **Mapping the circulation within the GRS.**
Appendix 3: **JunoCam at perijove-1: a global survey of Jupiter in 2016 August.**

Introduction

Opposition was on 2016 March 8, at declination 6°N, in Leo.

As usual, very many high-quality images were received from observers around the world. The list of observers is posted herewith as Report no.12 [ref.1].

The first usable image was taken on 2015 Sep.11 by Isao Miyazaki, who continued to image almost single-handedly throughout September. Paul Maxson started on Sep.23. In Oct., satisfactory resolution was possible and other observers joined in. From Nov. to June there was almost continuous coverage, often at high resolution. Special mention goes to Christopher Go in the Philippines and Tiziano Olivetti in Thailand, who both produced remarkably consistent series of v-hi-res images throughout the apparition, and to Phil Miles in Australia, who got remarkable results with a new 20-inch telescope, in collaboration with experienced observer Anthony Wesley. Damian Peach also produced top-quality images from observing sessions on Barbados from 2016 March 18-27 and June 4-20.

Image resolution declined as the planet receded during 2016 July, and by mid-August all observers had stopped, except for Miyazaki (who had imaged assiduously throughout the apparition, and continued till Aug.30) and Miles and Wesley. With the first operational Juno perijove due on August 27, Miles and Wesley continued taking infrared images before sunset up to 2016 Sep.3-4, and succeeded in getting a whole-planet map including the sub-Juno longitudes (see **Appendix 3**).

Galleries of images by various observers in March and April are in **Figs.1 & 2**; many earlier images were in Reports nos.3 & 4 [ref.1]. Images taken close in time show that different observers are consistent in recording fine details. A gallery of methane-band images is in **Fig.3**.

Methane-band images (at 889 nm) were particularly important this apparition because of the unusual display of methane-dark waves along the NEB. Only a minority of observers were able to detect these waves completely, apparently because they were using more selective filters and, in some cases larger telescopes. Narrower methane filters are more selective in visualising the higher atmospheric levels so that features of interest are seen without contamination from cloud features below [ref.2]. The nominal widths of the filters are listed in the Table of Observers. Miles' 8-nm filter (from Baader, on a 0.5-metre telescope) was the most reliably successful at detecting the waves; Go also detected them consistently although his filter was quite broad with 18 nm width (from Chroma). They were also well detected, in a few observations, by Germano (10 nm: Thorlabs) and by Peach (18 nm: Custom Scientific). However, the latter filter was used by several other observers with less success in detecting the waves, and Miles found it to be less selective than his 8-nm filter. It is possible that slight differences in the shape of the transmission band may lead to differences in the performance of nominally equivalent filters from different sources.

The same techniques were used as in the previous apparition [ref.3]. However, camera technology has continued to improve rapidly, with new models giving better sensitivity and hence better performance in mediocre conditions and better resolution. Most observers adopted the ZWO ASI120 camera just 2-3 years ago, but now it has been superceded by the ASI174 and 224; most observers switched to one or both of these for this apparition, and a few observers were 'test-driving' the ASI290 with even better results. Wesley and Barry, instead, acquired the Grasshopper3 camera from Point Grey Research and praised its high sensitivity and low noise level. Also this year, more observers started to use an automatic dispersion corrector (ADC), with good results.

The video acquired by the camera is then processed with several programs. Most observers now use Autostakkert!2 for the selection and stacking of images [ref.4]; many then use Registax for wavelet enhancement, and WinJUPOS for derotation over intervals of longer than 3 minutes, and other programs for further improving the appearance of the images.

The JUPOS team measured the images using WinJUPOS as usual, making 60981 measurements during the apparition. From these, they produced standard charts of longitude vs. time for spots in all latitude ranges. An annotated set of JUPOS charts is included with this report. Unless otherwise indicated, black points are dark spots, green points are bright spots, and red points are red spots. We extracted drift rates and latitudes from the JUPOS database for numerous features, large and small. The values for the major features and currents are summarised in **Tables 1 & 2**, and the values for all features are plotted in **Figures 4&5**. These charts comprise the zonal drift profile (ZDP) for the apparition, in comparison with the zonal wind profile (ZWP) as derived from spacecraft data.

Throughout this report, drift rates are given in degrees per 30 days in longitude system 1 (DL1) or 2 (DL2) (deg/mth). P. = preceding = planetary east (right in images); F. = following = west (left). Contrary to our previous practice, north is up in all images, for compatability with NASA images. Some maps with south up are posted as Supplementary Figures **(S-Figs.06, 07, 10-12).**

Our interim reports [ref.1] have already covered all important aspects of the apparition, with many illustrations – especially Report no.3 (covering the first half of the apparition) and Reports nos.8 & 9 (covering the latter half). Most of this material will not be repeated here. Our interim reports have also covered satellite transits (Report no.4 – including some recently added as Report no.4D), and a fireball on 2016 March 17 (Report no.7).

Five whole-planet maps have already been posted in Reports nos.3,8,9 and 10. Here we show a map from March 4-5, near opposition (**Fig.6**), and one from June 12-16, from Peach's Barbados images (**Fig.7**). A north polar projection of the latter map is in **Fig.8** (and a south polar projection in **Fig.23**). Maps from August 27, at the time of Juno's first perjove, are in **Appendix 3**.

The Hubble Space Telescope was used to make a pair of maps on two successive rotations on 2016 Feb.9, which can be 'blinked' to reveal fantastic detail in the planet's atmospheric currents [Ref.5]. Parts are reproduced here for v-hi-res views of some of the hi-latitude regions. Otherwise, all information in this report is from the amateur images, unless specifically stated.

There was a wealth of professional data during this apparition as Juno approached Jupiter to start its orbital mission. These included hi-res thermal-infrared maps made by Dr Glenn Orton and Dr Leigh Fletcher using some of the world's largest telescopes in 2016 Jan-Feb.

Northern Hemisphere

North Polar Region and N3, N4, N5 domains

Anticyclonic white ovals (AWOs) were tracked in each of these high-latitude domains.

N5 domain:
Four white spots were tracked here, ranging up to 62.5ºN; all had drifts very near the Cassini ZWP.

N4 domain:
Many white spots (often with dark rims) and small dark spots were tracked in this domain.
Two of the white spots (W1 and W2) were quite large ovals, and may have persisted from the previous apparition, although due to their unpredictable speed changes we cannot identify them with certainty. Most spots were on the broad retrograde peak (11 dark and bright tracks, including W2 and briefly W1: mean DL2 = +6.4 (±2.0), lat.50.4 to 53.2 ºN). From mid-Nov. to mid-Jan., W2 (at 52ºN) was very close to a white oval in the N5 domain (at 59ºN), both moving with DL2 = +9 to +10. However W1 and W2 also spent long intervals at higher latitude with large prograde drift (mean DL2 = -26.1 (±1.1), lat. 54.1 (±0.2) ºN), implying that they were AWOs. W1 and W2 are indicated in **Figs.8-10**.

N3 domain:
There were many well-defined tracks of both dark and white spots; two of the white spots lasted throughout the apparition. They all fell on a well-defined ZDP; most spots were on the anticyclonic side. As last year, the plot suggests a possible shift of the ZWP retrograde peak by about 0.5° southward.

N.N. Temperate (N2) domain *[see JUPOS chart N2]*

Three long-lived AWOs were still present in the NNTZ: LRS-1 (since 1993 or earlier), WS-4 (since 2003), and WS-6 (since 2010). They were described and illustrated in Report no.3, and are shown at v-hi-res in **Fig.9**. Methane images showed LRS-1 was very methane-bright as usual, WS-4 moderately so, and WS-6 only faintly detectable (**Fig.3**).
LRS-1, after the first few weeks of the apparition, was invisible except in v-hi-res images, as it had the same dull fawn colour as its surroundings, and only a very tenuous rim. (For this reason, the JUPOS chart has been supplemented by measurements of LRS-1 on methane-band images.)
WS-4 was still bright white, small and rimless.
WS-6 looked like WS-4 up to the end of Dec., but then became disturbed by turbulence at the f. end of a FFR in Jan. [Report no.3], and emerged with a dark rim and a slight orange tint. It retained an orangeish tint for the rest of the apparition, although it was much brighter than its surroundings (unlike LRS-1). But it was still only moderately methane-bright. If it is still reddish next year we will re-name it LRS-6.
WS-8 was a new AWO, which was bright white, small, and rimless, becoming more conspicuous during the apparition.

The NNTB was a continuous dark belt at almost all longitudes, though with variable width, from Nov. to Jan. There were just two gaps: the 'major FFR' (see below), and a pale cyclonic lozenge alongside the NTD.

The pale lozenge, in late Nov., was at L2 100-143, and dull white; thereafter it grew longer with a tapered p. end, and gradually became pale yellowish-orange. [A nice view of it on Feb.2 (Go) was in Report no.3 Fig.8.] After Feb. it drew p. the NTD and hi-res maps showed that its south edge -- a narrow dark NNTB(S) – was a chain of N2 jet spots.

Two sectors of NNTB faded somewhat in Feb-March and the 'minor FFR' developed (see below). One of these sectors was orange as it faded and two dark brown mini-barges persisted in it (L2 ~ 177 and 200). This sector revived in May-June as a very dark belt segment which spread p. from the minor FFR with the unusual drift of DL2 = -14 (at 36.9ºN; March-June).

There was still a faded sector from L2 ~ 10 (f. end of the major FFR) to ~153 (f. end of the pale lozenge), but even this had narrow streaks of dark NNTB(S) on the N2 jet with embedded jet spots.

Folded filamentary regions (FFRs): These turbulent cyclonic regions have been recorded in the N2 domain in spacecraft images, but only in the last few years have they been routinely resolvable in amateur images – in 2015/16, especially by Go, Olivarez, and Peach. So we can now record the time-course of FFRs and begin to interpret how they interact with other features. This is important, as it now seems likely that they are largely responsible for changes in most other features of the domain, viz. changes in the drift rate of anticyclonic ovals, production of retrograding dark spots, and production of prograding spots on the N2 jet [see below]. Our interpretations are well supported by the beautiful v-hi-res maps from Hubble on 2016 Feb.9 (**Fig.9;** Ref.5).

In 2014/15, there was a very large FFR in the NNTB from L2 ~ 280-360 [ref.3]. From 2015 Nov. to 2016 April, there was a large FFR in the NNTB at L2 = 330-15, very likely the same feature ('the major FFR') [plotted on the JUPOS chart; & see **Fig.9**]. LRS-1 was near-stationary at the f. end of the major FFR throughout Dec-Feb., then prograded past it in March-April. In May the FFR re-formed f. LRS-1. Following LRS-1 and the FFR, at L2 20-40, there were small dark spots with various negative and positive drifts (DL2 from -9.2 to +18.7) – probably analogous to the 'tail' f. oval BA and its STB segment in the S1 domain.

There was a smaller disturbed sector of NNTB, which sometimes appeared as a small FFR ('the minor FFR'), probably due to variations in the scale of the turbulent activity. It was identifiable as a small FFR in Jan., with WS-6 at its f. end and some disturbance apparently spreading p. from it, and likewise in early and late March; it spanned L2 ~≤253 to 268. But in Feb., mid-March, and mid-April, there was disturbance but no substantial FFR here. [**Fig.9**] (On March 12, a bright spot appeared in it and lengthened into a rift; meanwhile a dark spot was prograding from it [see JUPOS chart], giving rise to the prograding dark segment of NNTB described above.) WS-6 was near-stationary at the f. edge of the minor FFR throughout Jan-April, then prograded past it in May.

From April 23 onwards, the 'minor FFR' developed again as a mini-FFR *following* WS-6, with some disturbance still preceding WS-6. It remained so in May, sometimes being a longer FFR with WS-6 passing along its north edge.

It thus appears that both LRS-1 and WS-6 were held up at the f. edge of the respective FFRs for several months, then broke free and prograded along their northern sides. This raises the possibility that the mysterious irregular drifts of anticyclonic ovals, in this and other high-latitude domains, may be influenced by FFRs which could not hitherto be resolved. Possibly the natural speed of the ovals is prograding, but they can be held up temporarily by FFRs (which belong to the N.N. Temperate Current, i.e. near-stationary in L2), as well as by retrograding dark spots [refs.3 & 6].

N2 jet (NNTBs jetstream):

An intense outbreak of spots was still occurring on this jet; jet spots were numerous and widespread, both bright and dark. Most were in the range L2 ~0-180, and could be resolved as rings in v-hi-res images. From L2 ~180-260 (alongside the NTD) they were also visible, especially as rings or white spots. Few if any were observed from L2 ~ 260-350. We suggest that they were both created and destroyed by disturbance emanating from the major FFR.

Their distribution does not indicate interference by the NTD; rather, it probably indicates that they were being created and destroyed in specific sectors of the NNTB, as in 2013/14 [ref.7] and 2014/15 [ref.3]. Specifically, in 2013/14, N2 jet spots were appearing at L2 ~ 320-340, and we suggested they arose from disturbance spreading p. from a white 'mini-rift' or FFR which was at L2 ~ 5-35 in 2014 Jan-Feb; this may even have evolved into the present major FFR. In 2014/15, distinct jet spots were appearing at L2 ~ 200 and we suggested that they emerged from disturbance prograding from the major FFR (at L2 ~ 280-360). From 2015/16 April, the major FFR (at L2 ~ 330-15) was likely generating jet spots in the same manner, although the minor FFR (from L2 ~≤253 to 268) may also have affected the jet; the jet spots were only visible p. (downstream of) it. **[Fig.9]**

Taking all spots with DL2 faster than -65, the mean was -82.2 at 34.6ºN. Taking all spots with DL2 faster than -80, the mean was -87.6 at 34.7ºN [**Table 1**]. The latter represent the jet peak. While the dark spots cluster around the jet peak, the bright spots almost all fall on an anticyclonic gradient south from the jet peak, as expected. The distinction could be because the bright spots were larger and therefore their bright centres were resolved.

The fastest spot measured had DL2 = -95.5 at 34.6ºN; it was one of a newborn volley of 4 which arose at L2 260-280 in June (within the NTD). The next fastest, with DL2 = -91, arose at L2 ~ 180 in late Feb., and in April it decelerated and converted into a reddish ring (probably merging with another spot around May 1). This reddish ring was brown on April 26 and orange from May 10-25, with DL2 = -70 (±2) (Fig.9). It was probably slower than most because quite large and therefore southerly. Unlike most other N2 jet spots, this one passed the major FFR intact.

N. Temperate (N1) domain

The NTB had faded to near-invisibility, except for limited sectors of dark NTB(N), but there was still a prominent dark belt segment in the NTZ, called the N. Temperate Disturbance (NTD). The overall arrangement was similar to the past two apparitions and did not change much during the apparition. The domain could be divided into four longitude sectors (**Fig.10**), all drifting with the usual N. Temperate Current A (NTC-A):

1) A sector with one or more long dark streaks of NTB(N), sometimes very dark, though these sometimes faded away or revived. (These were D6, D7 and D10 in Table 1; notes on their evolution are given there.)

2) A 'rifted' sector in which the NTB appeared very turbulent at the highest resolution. This activity also waxed and waned. The rifted sector generates the NTD and marks its p. end, although this is often ill-defined. The extent of the NTD may vary on a short time-scale in accordance with the activity of the rifts. The rifted sector in Nov. became subdued in Dec., but revived in Jan. to become very long. In March a new one tens of degrees further p. replaced it, and thereafter the two sectors alternated in activity. They were separated by a dark streak (D11).

3) The NTD, i.e. a darkened sector of NTZ, substituting for the NTB. The f. end typically drifts with the NTC-A, but can shift from one locus to another. Thus it was very dark and well-defined from Nov. to Jan. [D13], but then withdrew ~75º p. in Feb (D12 in Feb-Mar.), and thereafter remained just p. AWO w3, becoming tapered in April [**Figs.9 & 10**]. The NTD was ~130º long in Dec., but contracted to only ~40º in Feb, then re-expanded to be 90-100º long in March–June.

4) Undisturbed sector, in which the NTB is almost absent, just a pale fawn band.

All features moved with the NTC-A [**Table 1** & JUPOS chart], but there was quite a range of speeds. Most features had DL2 between +14 and +20.5 with a mean of +17.1 (±2.7), but a minority (in NTB and in NTZ, both dark and bright) had DL2 between +25 and +36 with a mean of +29.4 (±4.4).

North Temperate Current B:
As in other recent years, there were a few small dark spots rapidly prograding in the faded NTB; the mean speed for 5 of them was DL2 = -69 (±4). They were in the undisturbed, pale sector of NTB, but were first seen just p. the dark streaks and may have originated further f.

N. Tropical domain

NEBn and the NEB Expansion Event (NEE) (**Fig.10**)

The North Equatorial Belt (NEB) underwent a partial 'expansion event', which started in 2015 as predicted (though slowly, and during solar conjunction), and the expanded sector covered 143º by 2016 Feb.; but then it stalled, and began to fade from both ends, until it completely regressed (**Fig.10**). This was unprecedented: all previously studied events have spread all around the circumference. For details see Reports nos.1-3.

This sector of NEBn f. WSZ had shown some transient broadening in 2014 Oct-Nov. (when a new slowly prograding rift developed p. WSZ), and it remained disturbed thereafter, sometimes with undulations, especially after the major rift passed it in 2015 March. This same sector broadened fully during solar conjunction. The expanded sector was ~95º long in Nov. and was ~143º long in Jan-Feb.

(from L2 = 45 down to L2 ~ 262); however the spread of the expansion had slowed down. The f. end remained almost fixed at L2 = 50 (Nov.) --> 45 (Jan-Feb.), at a prominent northward bulge of NEBn. The p. edge advanced almost imperceptibly past white spot Z (WSZ, which was prograding at DL2 = - 6 deg/mth) then stalled as an oblique boundary ~15º p. the centre of WSZ.

In April-May, the NEE was regressing. In Feb. it began to fade both at its p. end (around white spot Z) and at its f. end (around NRS-2). In late May it was only 90º long, and NRS-1 and -2 had disappeared. By mid-June it had completely regressed, so the NEBn edge appeared disturbed but otherwise fairly normal.

New spots in the NEE:

Outside the expanded sector, the NEBn still had irregularities, including two stable bulges, which may have persisted since the last apparition [see JUPOS chart; & Report no.3]. There were also two anticyclonic dark spots (ADSs) in the NTropZ in this sector up to March. One was called the NEBn red spot (NRS-1), as it was strongly reddish when first seen in Oct.; such dark reddish-brown anticyclonic spots are often produced before or during NEEs. It was a notable feature in Oct-Nov. but by Feb. was just a small grey-brown ring, oscillating in longitude with a period of ~2 months. The other ADS arose around Nov.22, apparently emitted Np. from an adjacent bulge; it became a small, very dark grey spot, oscillating with a period of 24 days.

New circulations formed quickly within the expanded sector. The f. end of the expanded sector rounded up to form a new red-brown anticyclonic oval, named NRS-2**.** The long-lived bulge just f. it contained a small 'barge' (dark brown cyclonic oval), from late Dec. into March, although this then became indistinct, while another one formed ~20º f. it in March. A barge also formed 29º f. WSZ, at least as early as Nov; in Feb., another barge formed just 12º f. WSZ, and as these travelled more slowly than WSZ itself, a third barge appeared f. WSZ in June.

So overall, at least four new barges persisted within the NEBn. All these features are typical of NEEs – including bulges which may contain cyclonic vestiges or precursors of barges, and ADSs which may be oscillating and grey or red-brown. They were documented in our reports for 2000/01 [refs.8&9]. They probably appear due to undulations of the NEBn retrograde jet, which generate cyclonic and anticyclonic circulations on each side: ADSs early in the expansion event, and AWOs and barges later.

White spot Z was still the most prominent AWO, embedded in yellowish surroundings. Its speed was unusually slow during this apparition, and fluctuating: DL2 = -6 to -7 deg/month. Exceptionally, its core became dark in methane images [Fig.3].

A chain of pale fawn-coloured patches at 14ºN, prograding with DL2 ~ -60, p. WSZ, may represent clouds forming and breaking rhythmically as the mid-NEB wind blows past the obstacle of WSZ.

Methane-dark waves:

Methane-band images showed a notable, widespread pattern of diffuse methane-dark waves on the NEB, which had only once before been observed so extensively, during the NEE in 2000/01 [ref.9]. The wave pattern was seen first and most clearly in professional images at 2.16 microns taken by Dr Glenn Orton & colleagues from 2015 Nov. onwards, but was also visible in amateur images at 0.89 microns [Reports nos.2,3,8,9]. (The complete pattern of these waves could only be recorded by observers with large telescopes and sufficiently selective methane-band filters, as noted in the Introduction.)

In Feb. the methane-dark waves were mostly spaced 18º apart (with two gaps) over the expanded sector and flanking regions [Reports nos.2 & 3]. In March and April [Fig.3], and in May [Reports nos.8 & 9], they were still present over much of the expanded sector of NEB and f. it (L2 ~ 300-70), but usually not around its p. end (although Go's image on April 1 shows them transiently revived there). In June, they were prominent from L2 ~ 190-355, and more subtly up to L2 $\geq$ 75, thus again covering the whole of the formerly expanded sector and beyond. The mean spacing in March-April [Fig.3] was about 20º (±1.5º), slightly longer than in Feb., and it seems to have been similar in June.

The well-observed wave pattern in 2000/01 was important because it showed that the methane-dark waves were the same as thermal waves (observed by Cassini, and previously from infrared observatories) and were linked to visible circulation patterns flanking the NEBn retrograde jet (observed by amateurs) [Refs.9,10]. In 2015/16, we did not see any obvious correspondence between the methane-dark waves and the underlying visible circulation patterns; however, this will be examined more thoroughly in a future study when amateur and professional images are combined to track the methane-dark waves over time.

NEB Rifts

From Nov. to early Jan., there were extensive rift systems in the NEB (Report no.3).
Rift system A was a very large one in late 2015. By early Jan. it had faded to a dull remnant, which was traced only to early Feb.
Rift B was a smaller one, first seen on Nov.19. It was a very bright compact white spot ("brilliant point") at 12.2ºN in mid-NEB at the f. end of rifted region A. This brilliant point persisted to the end of Nov. within a narrow oblique rift. There was again a brilliant point on Dec.30, quite southerly, generating a rift system which lasted until mid-Jan.
Rift C looked young on Oct.30, a brilliant point in a beautiful oblique narrow white rift, and it remained thus, shifting slightly southwards from 13.0 to 12.3ºN, until Dec.9. Thereafter, rift C expanded and it was the only rift system to survive through Feb. But it rarely showed bright spots in Feb., and in March it was a dull remnant consisting of pale streaks. However, tiny brilliant points still appeared in the southern NEB within it, although apparently not developing substantially. Examples are the six spots summarised in **Table 3** below (DL2 = -99 to -151, lat.11.8 to 10.5ºN).

Activity increased again around the end of March, in rift system C.
Rift system C appeared more active again then; its f. end (source?) had resumed a slow drift, but white spots within it in March-April had faster drifts, [e.g. W4b & W12 as listed in **Table 3 below**]. By late April, the rift system was a long but dull remnant. On April 28 a new, very southerly white point [W13] appeared at L2 = 270 in the f. part of it, and persisted as a single point at 10.3ºN until May 5, with DL2 = -158. Rift system C was then finished.

Table 3:

NEB Rifts, 2015-16					
Name	*Dates*	*Description*	*DL2*	*DL2*	*Lat.*
A	early Nov. to late Jan.	F.end of rifted region	-115 to -130		
B	mid-Nov. to mid-Jan.	W.s. then f.end rift	-85	-79	12,2
C	mid-Nov. to mid-Jan.	F.end of rifted region	-76		
		(accelerating from ~-66 to -80)			
White spots within C:					
	Jan-Mar.	Mean of 6 w.ss.		-99 to	11,8 to
		(tracks of 4-14 d)		-151	10,5
C (revived)	late Feb. to early April	F.end of rifted region	-86		
White spots within C:					
W4b	April 2-11	W.s.		-128,5	10,8
W12	April 7-14	W.s.		-123	11,7
W13	Apr.28-May 6	W.s.		-158	10,3
D [=W3]	Mar.30-May 6	W.s.(latterly in rift)	-98,5		12,0
		(accelerating from ~-90 to -103)			
E [=W14]	May 28-June 12	W.s.(latterly in rift)	-135		10,9
& W15	June 16 - July 3	W. rift	-142,5		10,4

Speeds (DL2, deg/month) are shown in separate columns for whole rift systems (left) and single white spots within them (right).

Rift D appeared on April 10, as a compact white spot. (It was on the track of an earlier tiny white spot, but this was absent on April 5-6. The tracks together are W3 in **Table 3**.) By April 13 it was embedded in a long narrow white rift. The brilliant point was conspicuous within this rift up to May 11. The brilliant point was methane-bright on May 2, but weaker and elongated on May 4 [images by Go]. But in June, rift D was only a dull remnant.
Rift E appeared on June 5, extending Sp. and Nf. from an isolated tiny white spot which had existed since May 15 with DL2 = -121. This white spot [W14] persisted with DL2 = -135 until June 14, but the rift [W15], with DL2 = -142.5, was becoming more elaborate up until the end of June.

The speeds of the rift systems ranged from ~ -66 to -142.5, without a clear trend, straddling the borderline of DL2 = -87 between slow (NEE-related) and fast (normal) speed ranges [ref.11]. So they do not fit cleanly into our previous understanding of the NEE cycles, in keeping with the premature end of the NEE itself.

Equatorial region

Table 4: Drift rates: Equatorial Region

Feature type	*Dates range*	*L1 range*	*DL1*	*N*
NEBs *(All values are approximate because of great variability in shapes and drifts):*				
Major dark formations	All	All	~0 to +18 (range)	10
Dark projections	Oct-Jan	40-100	-6 (estimated mean)	4
Dark projections	June-July	310-50	-9 (estimated mean)	4
Retrograding dark spots	Feb-March	various	+18 to +40 (range)	6
SEBn:				
Tiny d.ss. (chevrons)	Dec-Feb	All	-43,6 (±7,3)	7
Tiny d.ss. (chevrons)	Mar-May	All	-92,4 (±5,5)	7
Diffuse bands/gaps	All	All	-106 (±3)	5

NEBs

There were many large NEBs dark formations, as usual. They were quite variable in appearance, often being disturbed by mid-NEB rifts. On the JUPOS chart, the tracks were indistinct because of the irregular and variable shapes, but inspection of aligned maps **[Fig.11 & Suppl.Fig...]** confirmed the persistence of major features whose tracks were estimated on that chart.

Up to Feb.[Report no.3], about six of the dark formations were long and slow-moving, with DL1 ranging from ~ +9 deg/mth (the most distinct one) to +18 deg/mth. This was similar to the range in 2014/15 (+7 to +20 deg/mth). The sector from L1 ~ 290-100, which had only slim, fast-moving formations from 2015 April onwards, was largely the same until 2015 Nov-Dec., when slow-moving formations developed in its p. half, while in its f. half (from L1 45-105) a series of minor formations developed spaced 18º apart, with an intermediate-fast drift, DL1 ~ -6 deg/mth. However the intermediate-fast projections disappeared in Jan.

From Feb. to May, there were typically 11 major dark formations around the NEBs, with drifts over intervals of >1 month ranging from DL1 = 0 to +15 deg/month. Shapes ranged from prominent dark 'projections' to long low 'plateaux'.

In Feb-March, six very slow-moving dark spots appeared as NEB rift system C passed those longitudes (even though it was largely quiescent at that time), so they were probably partly entrained by the rift system; however they were short-lived. (Several other such slow-moving spots also appeared elsewhere; all are marked with blue tracks on the JUPOS chart. DL1 for these dark spots: rift-induced: +31, +39; others: +18, +21, +25.) These were all at 7-8ºN – the furthest north being at 8.1ºN – and a short-lived dark spot elsewhere at 8.3ºN had DL1 = +40. At essentially the same latitude (8.4ºN) was the only feature tracked with a strongly negative drift, a white spot with DL1 = -29.5. Clearly this range of speeds is not a function of latitude; all were on or near the peak of the NEBs jet, but the slow speeds were notably slower than the mean zonal speed according to the ZWP [Fig.4], while the white spot was much faster.

Of the major dark formations, the best defined were a series of four prominent 'projections' from L1 ~ 220-310 in March-May, spaced ~27º apart, with mean DL1 = +7 (±4). They were disturbed in late May when rift system D passed*, but most survived in some form into July.

[**Footnote*: On the maps, we can see one at L1 = 220 expanding greatly between April 20.5 and 24.6, and one at L1 = 280 expanding greatly between May 6-16, both of which later subsided again; and a notably large one 305-315 broke up in mid-May.]

Further f., some of the dark formations were slow-moving long low plateaux, sometimes very subdued, and were more decisively dissipated by the rifts passing in mid/late May. Short-lived dark projections with weakly negative DL2 then appeared in this sector (e.g. one with DL1 = -9 was typical).

SEBn

The SEBn had no major features, only the usual array of chevrons (tiny dark spots) at 7.2 (±0.2) ºS, which were generally irregular and short-lived. All appear to have been rapidly prograding in L1 as usual.   The JUPOS data were most complete for March-May, during which time we could track seven of the chevrons for up to 12 days, with a mean speed of DL1 = -92.4 deg/mth (±5.5 deg/mth, SD; range -86 to -100; N=7; u = +149.6 ±2.6 m/s). Many other sets of 3-4 points on the chart suggested that speeds in this range were widespread, as well as a few slightly slower ones. Also, the chart as a whole showed bands of chevrons alternating with diffuse gaps, with a speed of DL1 ~ -106 (±3) deg/mth (u = +156 ±1.4 m/s), matching the normal peak jet speed of ~155 m/s [refs.12 & 13].

In Dec-Feb., the measured tracks were slower, with DL1 ~ -43.6 (±7.3). These were short-lived (up to 8 days), except for one which lasted from Feb.28 to March 19. However, it is possible that there was no change in behaviour in March, as a few short tracks with similar slow or medium speeds were also suspected in later months, whereas at least one of the very fast bands (above) existed as early as Dec. The behaviour of the SEBn throughout may have been much as it was in 2010, with slower-moving chevrons appearing and disappearing transiently within the ubiquitously fast jet [refs.13 & 14], although the slow speeds were mostly slower than in 2010.

The JUPOS chart also showed a gap in the chevron pattern moving with DL1 ~ +20 deg/mth, up to the start of March; but it did not correspond to any visible structure, nor to any systematic trend in chevron speeds, so there was no South Equatorial Disturbance, even though the speed would be typical of one. Possibly this gap represented a more subtle wave on the SEBn jet. We recorded the same phenomenon in 2011/12 [ref.6].

Southern Hemisphere

South Tropical Domain

South Equatorial Belt (SEB)

Maps of the SEB are shown in **Fig.12**. White spot activity persisted in the usual turbulent region f. the GRS, to a variable extent. It was extended in March, then virtually disappeared in June, but recovered to a normal extent by August.

In Jan-Feb. the rifting f. the GRS was of normal extent and activity [Report no.3]. The short-lived bright spots within it were often methane-bright. The rifted region was then extended by new outbreaks of white spots at its f. end: one at L2 = 294 on March 1 [Report no.5], and another at L2 = 313 on March 25 (**Fig.13**).

However, this enhanced activity did not persist. Even as turbulence from the extended f. end prograded towards the GRS, new plumes ceased appearing in mid-May. This had previously happened in

2015 Feb., and we did not know whether normal activity would resume or not. There was a series of light spots prograding towards the GRS in June having appeared at higher longitudes; they were rather northerly and not methane-bright, but some of them brightened suddenly as they approached the GRS, on June 13 and 15. By July 4 it seemed that all activity might have ceased, but isolated white spots just Nf. the GRS again brightened briefly, and the region gradually became more disturbed, until by early August, it had a normal degree of white rifting.

The white spots in this rifted region had DL2 = -25 to -55 [mean -42: **Table 2**] and latitudes 12.5 to 16.5ºS [mean 14.9ºS], with no clear gradient, although they are visibly sheared as they drift towards the GRS. So as we observed during the 2010 SEB Revival [refs.15&16], these short-lived expanding plumes cover a wide range of latitude with only limited variation in speed.

Looking at higher longitudes, there were minor spots with DL2 ~ 0, followed by one or two red-brown mini-barges at 16.9ºS. The last two of these surviving from the previous apparition merged on Nov.28-29 [details in Report no.3]; then a new mini-barge appeared in April. The merged barge faded away rapidly during May [**Fig.12**; & Fig.X1 in Appendix 1]. Meanwhile a new white patch appeared ~20º f. it, slightly further north at 16.1ºS. Although such white patches have sometimes marked the northern edge of a faded barge, there was no sign of any such association in this instance. Another such white patch, even further f., had been tracked since the start of 2015, and may have derived from a barge in 2014 [ref.3]. All these features had typical S.Tropical Current drifts, i.e. slightly positive DL2.

SEBs jet

Report no.3 gave details & images of 5 white spots or rings (vortices) on the SEBs. An updated listing [**Table 2**] gives mean DL2 = +131.3 for these 5 vortices, at 20.6ºS; plus one slower one, DL2 = +118.5, 21.1ºS. They were each tracked until they entered the Red Spot Hollow (RSH), on various dates from Nov. up to Feb.8, when the last one arrived. Report no.3 also gave details of their interactions with the GRS.

After mid-Feb., the nature of activity on the SEBs jet changed (Fig.12). There were no more distinct vortices. Instead, wave-trains developed, sometimes with high amplitude, with wavelengths of 4º to 6.5º longitude. They were commonly seen from late Feb. at least until June, although they were variable and restricted in longitude. We therefore undertook careful analysis of some of the most regular examples. The results were very clear (see **Appendix 1**). All the wave-trains were retrograding much more slowly than the normal jet peak, having speeds of DL2 = +68 to +95. When the speeds were plotted against the wavelengths, they agreed very well with the correlation that we established for the 2010-2015 data [ref. 17].

Remarkably, we also found concurrent speeds of DL2 ~ +150 -- much more rapidly retrograding than the wave-train, or even than the known jet peak! Three individual white spots or bays, plus one pair, were found to have this speed, often moving through wave-trains that were retrograding about half as fast. We also confirmed that in late 2012, when similar small white spots had similar rapid speeds, at least one of them co-existed with a slower-moving wave-train, exactly as in 2016. Also in 2016, gaps between the slowly retrograding wave-trains were also moving with DL2 ~ +150, which may represent a group velocity for the wave-trains, and/or, the actual peak velocity of the jet. These extraordinary results are presented and discussed in **Appendix 1**.

STropZ

The northern STropZ (20-23ºS) was occupied by a streaky dark grey band from L2 ~ 0-230; we refer to it as the SEB(SS). The grey spots and streaks on it were retrograding with the S. Tropical Current and fit well onto the ZWP. Most had DL2 between 0 and +20, with a mean of +9.2 at 22.9ºS. There were also a few faster or slower. One tiny streak was emitted from the dark rim of Oval Q around March 1, and retrograded at DL2 = +42 --> +24 until it slipped into the RSH on April 1.

'Oval Q' was an anticyclonic ring which started out in Jan. as a SEBs jetstream spot at 21-22ºS (DL2 = +73). It gradually drifted southward to 23ºS and decelerated in accord with the ZWP, until it halted ~20º p. the RSH. It was then a prominent dark ring. Such a spot has often existed in this position; we have dubbed previous examples 'Oval Q'. But this one rapidly shrank during May, although it probably remained present at L2 ~ 210-220 at least until mid-June.

Great Red Spot (GRS)

The GRS was at L2 = 242 at opposition. Its drift in longitude was exceptional: mean DL2 = +1.5 deg/month during 2015 (March-Dec.), but +1.9 deg/month in 2016 (Jan-Aug.).
(It oscillates with a constant period of 90 days, so the mean drift rate can only be determined over longer intervals.) This is much slower (more positive) than ever before when the SEB is normal.
The mean length was 14.0º (±0.6º), with real variations (**Fig.14**). It was particularly small in Jan. (13.1º ±0.6º), and again in June-July (13.6º ±0.4º), but otherwise was >14º long. The width in latitude from Nov. to Feb. was 9.7º (±0.23)º. Despite its small size it still interacted with incoming SEB jetstream spots, as described in Report no.3.

The GRS was still exceptionally small and dark and red. Richard McKim commented that, visually, "the GRS was the darkest and reddest I can recall, having started observing in 1973". Kuniaki Horikawa said that it "is the reddest and darkest in the last 30 years.... close to vermilion rather than orange", although not as dark as in the mid-1970s.

The GRS is an anticyclonic vortex, and its internal circulation has been monitored from amateur images since 2005. With the improved images in 2015 and 2016, it can now be monitored not just from occasional single streaks, but from smaller-scale cloud textures that were previously only resolvable from space (e.g. in Figs.13 & 18).
The circulation was several times detected over a span of just 1-2 hours as the GRS crossed the disk [Reports nos. 3 & 6 – q.v. for hi-res images]. On one of these transits it was possible to measure the rotation rate as 4.0 (±0.3) deg/hr, implying a period of 3.73 (±0.26) days [Report no.6], which is the same as we found by measurements of single features in 2014 and 2015.

Now, Michel Jacquesson has taken this analysis further by measuring multiple subtle features in the GRS on image pairs taken ~10 hours apart, and plotting their rotation rates as a function of distance from the centre. His measurements in 2015 and 2016 gave almost identical results. (***Appendix 2)*** Within the uncertainties of the measurements, the circulation is indistinguishable from solid-body rotation in the outer half of the GRS. The mean rotation rate is 105 (±16) deg/day, implying a rotation period of 3.4 (±0.5) days. The absolute speed is thus proportional to radius, up to 150 (±16) m/s. Although the results have limited precision, the internal flow field has indeed been recorded in our ground-based images, and there has been no significant change in the wind speeds since early 2014.

South Temperate Domain

For previous history see our long-term reports [refs.18 & 19].

STBn jet:
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.

STB:
The STB was completely absent, as there was no substantial activity on the STB(N), and all three structured sectors were inconspicuous. They were as follows:

(Segment D): Oval BA and the dark spot f. it. **(Fig.15)**

After the collision of a STB dark segment with oval BA in 2013, we were expecting the remainder of the dark segment to shrink to a small dark spot, and oval BA to decelerate [ref.20]. These changes did occur, rather belatedly, in early 2016.

By Feb., the dark streak on the f. edge of oval BA had shrunk to a very small spot [Report no.3_Fig.3], <~5 deg long, and accordingly [ref.19], oval BA showed every sign that the turbulent activity f. it has finally declined. It had no dark rim, the STB(N) p. it was quite faint, and there were only a few dark spots Sf. it; and, most distinctively, it had decelerated. These changes happened later than expected, probably because the dark streak's turbulent activity persisted. Actually, in Feb. the dark spot was still disturbed, still emitting some dark spots Sf. it and dark material around oval BA and on STB(N) p. it; but in March it quietened down. It did not become an inert 'barge'; v-hi-res images still sometimes showed it disturbed and emitting spots Sf. it, but this was all on a very small scale.

Oval BA lost its dark rim temporarily in Jan. and permanently in April, and gradually became redder during the apparition until by June it was as strongly red as it has ever been.

In retrospect, oval BA had DL2 = -11.0 (±0.5) since the start of Feb., with only short-term fluctuations. This slow drift is typical when there is no turbulent STB segment f. it, as predicted [refs.18-20]. The length of oval BA (from the images in Fig.S4) was 7.8 (±0.4) deg, measured as the outer diameter of the white oval; the orange annulus within it was 5.8 (±0.3) deg long.

The dark spots in the Sf. tail **(Fig.15)** were strongly retrograding, with DL2 = +11 to +36, at 31.3 to 32.5 ºS (Fig.20). These speeds were more positive than usual, matching the jet peak observed by spacecraft [see below.] 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) (Fig.15). This was a typical origin of a small anticyclonic oval [refs.18 & 19]. There was also a rimless white spot f. it in March-May. However it is not clear whether either of these survived after mid-May.

(Segment E): STB Ghost **(Fig.16 &17)**. This is a cyclonic circulation, and is still a pale blue loop, but methane-dark - just like the former Segment C (STB Remnant) [refs.18 & 19].

(Segment F): STB Spectre **(Fig.S6)**. This began life in early 2015 as DS5, a small, extremely dark spot within an oblique cyclonic blue loop. As previously suggested, it developed exactly like the STB Remnant in 2004 and STB Ghost in 2012 [ref.19]. 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 Feb. **[**Report no.3_Fig.12]. 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); and thus it has become a near-duplicate of the STB Ghost, so it was named the STB Spectre.

The SSTBn and STBs jets and recirculation at the STB Ghost and Spectre:

While the STB Ghost and Spectre, like the earlier STB Remnant [ref.18], are cyclonic circulations, we have repeatedly observed anticyclonic recirculation due south of them, as small dark spots prograding in the SSTBn jet are deflected retrogradely in the STZ [refs.18 & 19]. We have noted further evidence for the circulations in both senses in HST images in 2015 and 2016 [ref.21]. 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. One of them arose shortly p. oval BA in Nov. and passed DS5. Thereafter, when DS5 had pulled ahead of BA and evolved into the STB Spectre, the SSTBn jet spots arose at or just p. the Spectre. They had initial speeds of DL2 = -116 (±7) deg/mth (n=5), which is faster than all previous measurements for this jet except by New Horizons. (We have previously observed mean peak speeds averaging -110 (±2), with a maximum of -114 in 2011/12. The peak speed was -94 from Cassini and -126 from New Horizons. --Ref.22). They all decelerated after 2-3 weeks, en route to the STB Ghost; as they did so, two of them crossed and some others merged. They drifted slightly northward at this time although the ZDP was unusually shallow [see JUPOS chart & Fig.20]. None of them got past the STB Ghost.

The first spot to reach the Ghost, in Jan., halted near the p.[*sic*] end of the Ghost, and then probably disappeared. Then in April-May a volley of five spots (here numbered D2 to D6) arrived in succession, producing complex appearances; our analysis shows that all of them recirculated to retrograde (temporarily) in the STZ f. the Ghost. These events are shown in [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 (except for D5 – but see below). After recirculation, D2 merged with a pre-existing stationary spot which then faded away; D3 became retrograding G1 (DL2 = +13); D4 became retrograding G2 (DL2 = +16), which then merged with G1; D5 faded away but later reappeared in the retrograding sequence; and D6 became G3. But G1, G2 and G3 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 for G1, then -12 for merged G1/G2). 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 [Report no.3] 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 with the STC, ~20-30º f. DS5. These two spots (S1 and S2) persisted till April-May, mid-way between the Spectre and oval BA, with typical STC drifts of DL2 = -10.5 and -4 --> -19 respectively. 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.18 & 19].) 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.18 & 19]. Possibly this drift reversal occurs when the spots evolve into more substantial vortices, which then adopt a more stable position in the STZ.

S2 (S.S. Temperate) domain

There were nine long-lived AWOs here, which continued to follow the general rules described in our long-term report [ref.22]: "There have always been between 6 and 9 long-lived AWOs in this domain from 1986 to 2013,..... In contrast, transient AWOs also appear (...the recent frequency has been about one every two years), but do not last more than 1-2 years." Of the 11 AWOs that were present in 2014/15 [ref.3], A7a and A7b were new and small and disappeared again. The 9 long-lived ones (numbered A0 to A8 for historical reasons) continued to converge into a tightly spaced array (A6- - -A0- - -A5), except that A5 (at the f. end) increasingly separated from the others [**Fig.22** & JUPOS chart]. This was initially because of the white cyclonic sector between A4 and A5, which was rapidly expanding as they do, but this became less bright during April-May (see below), leaving A4 and A5 almost 60º apart. The other eight ovals continued to converge until they occupied only 133º longitude (centre to centre, for a mean spacing of 19.0º) at the start of August. However, a new light (though not white) oblong appeared between A1 and A2 during April-May; then a new white oblong appeared between A3 and A4 in August [IR image by Miles, Aug.28], and A3 and A4 began to move apart again.

In cyclonic latitudes, the AWOs are usually separated by various cyclonic structures, especially FFRs, as revealed by the Voyager images. The best amateur images are now sufficiently good to resolve these structures, and the arrangement in 2016 Jan.-June [Fig.22] was:
--between A6-A7-A8-A0: FFRs;
--between A0-A1: cyclonic white oval, oscillating;
--between A1-A2: off-white oblong developing (pale fawn colour);
--between A2-A3: FFR;
--between A3-A4: short bland section [Jan-March?] in which a narrow belt segment became increasingly dark (to June) before turning white (August);
--between A4-A5: long white oblong until March-April, but then more disturbed and encroached upon by a dark belt in SSTZ with slow-moving dark spots or waves along the boundary;
--f. A5: large FFR (Jan.-May); seems quieter in June.
The chronicle can be extended to late August with the JunoCam images **[Appendix 3]**, in which there was still a large FFR f. A5, and the only notable change was the new white oblong between A3-A4.

In comparison with the arrangement in 2015 March [ref. 3], some of these sectors were of the same cyclonic type, but about half had changed. Given these frequent changes and the limitations on resolving FFRs, we cannot say definitely whether FFRs persisted through solar conjunction.

For the long-lived AWOs, the mean DL2 was -28.4, at 40.6ºS. There was also a new, small AWO remote from the others, oscillating with irregular periods of 0.8—2.3 months. On June 20 it was apparently merging with an even newer and smaller AWO p. it (Fig.21).

Several slow-moving dark spots or streaks were recorded, in the now-shaded interval between A4-A5, and f. the new oscillating AWO: mean DL2 for the best 3 tracks was -13.9, at 40.6ºS. Hi-res images in late April suggested that in both these sectors, the slow-moving features mayhave been waves on the retrograding jet separating a whitened 'SSTB' from darkened 'SSTZ' [Figs.3 & 17].

S3 domain

The S3 prograde jet was visualised by just 5 short-lived white spots, four of them having DL2 = -102.8 (±1.2), mostly at latitude 43.8ºS.
In the cyclonic domain, at 46.0ºS, was a white spot, with the remarkable prograding speed of DL2 = -30 --> -25.

The main features of the S3 domain were two AWOs with wildly varying drifts, and a long-lived sector of retrograding small dark spots, which we propose is due to a long-lived cyclonic disturbance.

A notable feature of the S3 domain is a slow-moving sector in which retrograding small dark spots are present, at 49ºS. In 2015/16 the dark spots in this sector had DL2 ranging from +5 to +29, with an average of +16.4 [Fig.22]. But the sector as a whole drifts at a different rate. The same sector was present in 2014/15, and over the two apparitions it drifted with DL2 ~ -10.5. A similar sector existed from 2005 to 2010 with DL2 ~ -7.5 [ref. 22]. These (very approximate) drift rates are close to the canonical slow current for the domain, the S3 Temperate Current [ref.22]. By analogy with the S. Temperate and other domains, we have suggested that this sector represents a 'Sf. tail' of retrograding dark spots emitted from a long-lived turbulent cyclonic formation, which is usually too inconspicuous to detect from Earth [ref.22]. The 2016 observations support this hypothesis. In March there was a distinct dark bar at L2 ~ 50-60, at ~47ºS, just p. the retrograding sector and with a similar drift, DL2 = -12 (±2). In later months, no such bar was tracked, but maps showed an oblique dark streak in similar position [Fig.22]. We think this was a long-lived disturbance that continuously generated the retrograding spots.

Indeed, Hubble maps made on 2015 Jan.19 and 2016 Feb.9 [Refs.5 & 23; Fig.22] showed a FFR in the relevant position p. the retrograding sector, which was probably generating the spots, and which could sometimes have appeared as a dark bar or streak in ground-based images. In both years, the Hubble maps also showed an even larger FFR further p., which may also have been generating some of the spots.

There were two AWOs. S3-AWO-1 (Figs.21 & 22) is very long-lived. [ref.22] Initially it was oscillating regularly with period ~ 1.0-1.2 months; then it halted at L2 = 312 from early March to mid May; then it suddenly adopted DL2 = -41 (±2), before halting again at L2 = 246 for the whole of July. It was only faintly visible in methane images (Fig.3).

S3-AWO-2 was due north of S4-AWO-1 from Nov. to Feb. It may have been ~20° p. it in 2014/15, but its identification is uncertain as it was inconspicuous and sparsely recorded. It was much better tracked in 2016 March, when it decisively pulled ahead of S4-AWO-1 with DL2 = -41. But then it decelerated and reversed its drift to DL2 = +5 --> +10 (April-May). By the start of June it was again just north of S4-AWO-1, and both ovals again developed rapid drift. It remains a mystery why these apparently unconnected AWOs in the S3 and S4 domains so often remain close in longitude. Another such coincidence occurred around March 1, when both S3-AWO-1 and S4-AWO-1 suddenly halted in L2 (and stopped oscillating); S3-AWO-2 followed suit several weeks later. However, these timings may have been coincidental. Each of the decelerations occurred when the AWO approached a small retrograding dark spot (see JUPOS charts). We have previously recorded similar events in the S3 domain [ref.6] and N2 domain [ref. 3], showing that these apparently minuscule retrograding spots can have a surprisingly strong effect on AWOs encountering them.

Waves on the S4 jet:

Another remarkable feature of the JUPOS chart for the S3 domain was a band of short (~10 days long) prograding tracks at 51.7°S, 15° apart in longitude, individually with DL2 ~ -20.5 to -30.5, but collectively with DL2 ~ -112 (±12). The map of March 4-5 [Fig.22] shows that this was a wave-train on the SPRn edge, which is a permanent, sharp visible boundary that coincides with the S4 jet. From spacecraft, the S4 jet peak has mean DL2 = -143 at 52.7°S. Thus, these features were waves on the S4 jet; the individual speeds represent the phase velocity while the collective speed is the group velocity. The wave-train apparently persisted, because when its extrapolated track passed two dark spots in the retrograding sector, they suddenly accelerated to DL2 = -22 and -35, shifting to 50°S (in accord with the ZWP). Including these, the mean phase velocity was DL2 = -27 (±7) (n=5). The same wave-train can probably be recognised on the Hubble map of Feb.9, and the ground-based map of April 28-29 [Fig.22], with a group velocity of DL2 ~-94 deg/mth.

Such waves on the SPRn edge are occasionally visible in amateur images, and more commonly in Hubble images [e.g. Fig.22, & refs.22 & 23], but their phase and group velocities have been measured only once before. A similar but subtle wave-train was detected in Voyager 1 ultraviolet images: latitude 53.1°S (±0.8°), wavelength 15.5° (±1°), n = 23, phase speed DL2 = -23 (±6.6) deg/mth. [ref.24].

These waves are not related to the waves that are often seen on the edge of the methane-bright South Polar Hood at ~67°S [refs.24 & 25] (e.g. some in Figs.3 & 13).

S4 domain

Here were few features other than three AWOs, including the long-lived methane-bright reddish oval, S4-AWO-1 (Figs.22 & 23), which has existed at least since 1987 [ref.22]. S4-AWO-2 has probably existed since 2010 [unpublished JUPOS data]. S4-AWO-3 appears to be new.
All three had oscillating tracks with irregular periods of ~1.0—2.5 months, interspersed with longer intervals when the speed was either fast (e.g. AWO-3, Oct-Jan., DL2 = -24, prior to merging with another small AWO) or close to L2 (e.g. AWO-1, DL2 = 0, late Feb. to early May). It may be no coincidence that AWO-1 ended its oscillating track and halted at L2 = 250 just as it encountered a sector containing slow-moving dark spots (DL2 ~ 0, ±3; n=2), as noted above. Although these were sparsely observed, the Hubble map [Fig.22] suggests that they comprised a ‘Sf. tail’ f. a series of FFRs, similar to those in the S3 domain.

South Polar Region

Finally two ovals even further south were tracked for 3-4 weeks each:
one in Dec., DL2 = -33.6, at 67.7 (±0.3) °S; and
one in Feb-Mar., DL2 = +16.4, at 71.3 (±0.6) °S.

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Figure legends

Figures 1 & 2. Galleries of images in 2016 March and April, all around the planet. North is up in all maps and images.

Figure 3. Methane-band images from March and April. Similar sets have already been shown for Nov-Feb.(Reports no.2&3) and May-June (Report no.9). This is a selection of images from observers with more selective filters which clearly showed the methane-dark waves on the NEB (indicated by cyan dots in the top row). Other observers with less selective filters (e.g. Paul Maxson, Martin Lewis, Marc Delcroix, Christophe Pellier, Manos Kardasis) also took good images on which features such as the methane-bright ovals can be tracked but not the NEB waves. Other features labelled are anticyclonic ovals in the NNTZ, NEBn (white spot Z; exceptionally, it is methane-dark), and all southern domains. The STB Ghost and Spectre are cyclonic features and are methane-dark. The polar hoods are clearly visible and some of the images show waves along the edge of the south polar hood.

Figures 4 & 5. Complete zonal drift profiles (ZDPs) for N and S hemispheres. The continuous pale blue line is the zonal wind profile (ZWP) as derived from Cassini spacecraft data [Porco et al., 2003]. All reliable track segments are plotted; for many spots we measured multiple track segments as the drift rate varied.

Figure 6. Map on 2016 March 4-5, near opposition. North is up in all maps and images. A copy with south up is **S-Fig.06.**

Figure 7. Map on June 12-16, made from images taken by Damian Peach on Barbados. For N and S polar maps, see **Figs.8 & 23**. A copy with south up is **S-Fig.07.**

Figure 8. North polar projection map on June 12-16, from the same data as Fig.7. (Compare with map on April 28-29 in Report no.9.)

Figure 9. V-hi-res images of the north polar region, especially showing the major anticyclonic ovals (purple arrows) and FFRs (green brackets) in the N2 domain. At top is an excerpt from a Hubble map [ref.5] (with exaggerated colour) showing these features in more detail. (Also indicated on the images are an N4 AWO, N2 jet spots, and features of the NTD.)

Figure 10. Maps of the northern hemisphere from latitudes 0 to +50, labelled for major features, especially in the N2, N1 (N.Temperate), and N0 (N.Tropical) domains. All except the final map are in equirectangular projection, aligned in L3, plus L2 scales in some cases. All maps were made by Marco Vedovato except the final map and the Feb.9 Hubble map [ref.5]. Similar maps up to Jan.31 were shown in Report no.3. The same maps plotted in L2, with south up, unlabelled, are shown as **S-Fig.10.**

Figure 11. Maps of the NEB showing changes in the rifts and NEB dark formations during March and April, aligned in L1, with north up. All maps were made by Marco Vedovato. These are just examples from a complete series covering Feb. to June, with south up, shown as **S-Fig.11.**

Figure 12. Maps of the SEB, Feb. to May. (Also see main map in June.) Note the expansion and later quiescence of the SEB rifted region f. the GRS. The merged barge is marked, as is oval Q in the STropZ. Wave-trains on SEBs are marked by a cyan bar immediately above them; letters correspond to individual wave-trains described in the Appendix. Magenta arrows indicate a very rapidly retrograding tiny white spot [g] on SEBs. The same maps plotted in L2, with south up, unlabelled, are shown as **S-Fig.12.**

Figure 13. Extension of the SEB rifted region f. the GRS by a new white spot on March 25 (blue-grey arrow). It was visible as tiny spot in the image by C. Go on March 25, though it was first noticed in the image by A. Lasala on March 26. It was methane-bright on March 28 (C. Go) and 29 (M. Kardasis). In

Go's March 25 image, also note hi-res views of the GRS interior, DS5/STB Spectre, big FFRs in the S2 and S3 domains, and S4-AWO-1.

Figure 14. Length of the GRS during 2015/16 (monthly means from hi-res images, with standard deviations).

Figure 15. Oval BA and associated dark spots, 2015 Dec. to 2016 June.

Figure 16. The STB Ghost, 2015 Dec.25 to 2016 April 1.

Figure 17. The STB Ghost, 2016 April-June, showing SSTBn jet spots D2 to D6 arriving and recirculating back into the STZ. (D5 was not seen as it recirculated, but it then reappeared in the STZ.) These images also show SEBs wave-trains, as indicated in Appendix 1.

Figure 18. STB spot DS5, reddening and fading, passing the GRS, and evolving into the STB Spectre.

Figure 20. Zonal drift profile (ZDP) for the S. Temperate domain including SSTBn jet, 2015/16. The dashed grey curve is the Cassini ZWP from Cassini. Note that SSTBn jet spots (blue diamonds) have a much faster jet peak, although they adhere closely to the ZWP on the north side of the peak. Pale mauve lines connect points for individual spots circulating at and f. the STB Spectre; note that they lie systematically above the Cassini ZWP. (Curiously, this is less so for the spots which had reverted from retrograding to prograding (STC), i.e. DL2 ~ 0 to -25 – although each spot did change latitude when it recirculated in the appropriate sense.) Points for the ends of the STB Ghost naturally have a mean speed matching the centre of the Ghost despite their different latitudes.

Figure 21. V-hi-res images in June showing interactions of small spots south of the GRS. Red arrows: Merging S2-AWOs. The new small AWO encounters an even newer and smaller one, and they likely merge after June 20. Pink arrow: Dark spot in STZ retrograding f. the STB Spectre, having recirculated from SSTBn on June 3. White arrow: S3-AWO-1.

Figure 22. Maps of the high southern latitudes (Equirectangular projection, north up); aligned in L3 with L3 scales at top and bottom and L2 scales also given. At top is a map from Hubble on 2016 Feb.9, shown at the same scale as the ground-based maps, plus a full-size excerpt covering the most interesting region of the S3 domain, and a similar excerpt from a Hubble map on 2015 Jan.19 [refs.5 & 23]. The following features are labelled: In the S2 domain, the nine stable AWOs. In the S3 domain, AWO-1 and 2, and the sector of retrograding dark spots, with the dark streak which may mark a FFR that generates them. In the S4 domain, AWO-1 (reddish oval).

Figure 23. South polar projection map, 2016 June 12-16, from the same data as Fig.7. (A similar map from April 28-29 was posted in Report no.9.)
