Jupiter in 2019: Report no.9

John Rogers (2020 Jan.)

Summary

This is a fairly detailed report covering the last 2/3 of the 2019 apparition, which can serve as a draft for our final report. It is based on amateur images but also incorporates some results from JunoCam.

A Zonal Wind Profile is presented, derived from Hubble images on June 26-27, giving speeds for the major jets.

North and south polar projection maps are presented, from both amateur and JunoCam images; features were tracked up to ~72°N and ~75°S. A large AWO has been tracked in the N5 domain.

N2 domain: Five anticyclonic ovals in the NNTZ were tracked; one AWO has turned reddish and a new small reddish oval appeared. Changes in NNTB segments are documented.

The NNTBs jet outbreak is still active.

N. Temperate domain: Most of the NTB is very pale, but there is still a rifted sector, which generates the dark N. Temperate Disturbance f. it.

The NTBs jet speed is measured and predicts a new super-fast outbreak in 2021.

N. Tropical domain: The NTropZ is now all white. The NEB is a dark brown belt of normal width, with no major rifts until late November.

On the NEBs, a regular array of typical large dark formations was prominent in 2019, with DL1 around +5 deg/mth. There were also some short, faster tracks, e.g. DL1 ~ -20 deg/mth.

Equatorial Region : The strong ochre colour of the EZ was the most impressive feature of this apparition. It had begun in spring, 2018, and was most intense for the first six months of 2019. Since the summer, it may be fading.

S. Tropical domain: The SEB consists of three fairly narrow dark components. Unusually, the northern half of the belt is largely quiet and whitened (esp. f. the GRS), while the southern half shows normal activity of the post-GRS rifting and SEBs jetstream spots. There are two 'white barges' in southern SEB, both probably derived from earlier brown barges.

There have been many retrograding SEBs jet spots (rings), with normal speeds for the jet, as well as slower-moving wave-trains.

GRS & flakes: A remarkable phenomenon in 2019 was the repeated emergence of 'flakes' of red, methane-bright material from the GRS, typically induced at its f.(W) end several days after a retrograding SEBs ring had entered the Red Spot Hollow at the p.(E) end (as described in our previous reports up to no.7). As of late July, there were no further rings on the SEBs for a long distance, and indeed no more flakes were produced in August. Then, a series of 7 SEBs rings arrived from Sep.8 to Oct.17, and each one apparently led to a flake appearing at the f. end 3-6 days later. Also, from Sep.21 onwards, small protrusions emerged from the p. end of the GRS, probably flake material that had travelled round the S side. These phenomena were probably similar to those recorded at higher resolution earlier in the year.

The GRS had shrunk in April-May, and in June it was very small, only 12.1 deg long. Its length then recovered somewhat, reaching 14.0 deg. in late Oct. Its mean drift rate throughout 2019 was DL2 = +1.9 deg/mth, unaffected by the flaking events.

The dark grey-brown ***S. Tropical Band*** formed in April, and it elongated rapidly and combined with the dark STB(N) p. oval BA so as to extend almost completely around the planet in July. Then it began to decline, and it faded away in August. Two anticyclonic rings had formed on it p. the GRS in May-July, and persisted up to Oct.

S. Temperate domain: ***Oval BA*** is still white, and fast-moving (mean DL2 = -14.2 deg/mth), with a short dark turbulent STB segment f. it, which presumably generates the dark spotty bands in STZ Sf. it and on STB(N) Np. it. ***The STB Spectre*** had low contrast and continued to lengthen rapidly, attaining a length of 110° by Nov.3, when JunoCam confirmed its structure.

S2 domain: There are still 8 AWOs. Two of the cyclonic intervals between them were white oblongs. In other intervals, we document dark bars and turbulent regions.

S3 domain: We track four AWOs in 2019, and some retrograding dark spots.

An impact flash was detected on 2019 August 7, the sixth since 2010.

Appendix: **'Towards a new three-year weather forecast for Jupiter'**

Supplement: **JUPOS charts for the major domains, annotated.**

Introduction & Acknowledgements

This is our first report covering all latitudes since 2019 Report no.4 in May; subsequent ones have concentrated on the events around the GRS. This report will give an account of events throughout the apparition of 2019, insofar as they have not been already covered. It can serve as a draft for a final report on the apparition. It is largely based on the JUPOS charts up to Oct.11, but with some data on major features added from the newer charts up to Nov.29. The **Supplement** contains a set of annotated JUPOS charts, each with an aligned strip-map (with south up).

Opposition was on 2019 June 10 -- the most southerly opposition of the present jovian year. Southern-hemisphere observers produced many excellent images, though in the later months Australian observers were impeded by poor weather and then by rampant wildfires, so it was Clyde Foster in South Africa who produced most of the hi-res coverage from mid-October onwards, ending on Dec.2. (Niall MacNeill in Australia continued until Dec.6, just 3 weeks before solar conjunction. These late images were made in daylight.)

Results are from ground-based amateur images unless otherwise stated. Some references are made to JunoCam images [see the JunoCam web site: https://www.missionjuno.swri.edu/junocam, and our reports on this site at: https://www.britastro.org/node/17650] and to the Hubble OPAL maps of 2019 June 26-27 [https://archive.stsci.edu/prepds/opal/].
Combination of data from all these sources has been especially useful for making sense of the phenomena in some of the higher-latitude domains. Juno's perijoves are listed in this Table:

Perijove	*Date*	*Features include:*
PJ17	2018 Dec 21	Oval BA
PJ18	2019 Feb 12	GRS & SEB rifts
PJ19	2019 Apr 6	(Southern latitudes only)
PJ20	2019 May 29	NTD
PJ21	2019 Jul 21	WSZ; GRS & SEB rifts
PJ22	2019 Sep 12	NN-WS-6
PJ23	2019 Nov 3	NTD; SEB 'white barge'; STB Spectre

As usual, this report mostly uses System II longitude (L2), although L3 scales are given on maps for compatability with spacecraft data, and L1 is used for the equatorial region. Drift rates in L1 or L2 (DL1, DL2) are given in degrees per 30 days (deg/mth). DL3 = DL2 + 8.0 deg/mth. P. = preceding (east), f. = following (west). Latitudes are planetographic. North is up in illustrations unless otherwise indicated. However, drift charts (especially the JUPOS charts in the Appendix) follow our standard convention in being aligned with maps with south up. Unlabelled versions can be provided if needed.

This report is the result of work by numerous amateur observers around the world (the list will be posted shortly); by the JUPOS team (Gianluigi Adamoli, Rob Bullen, Michel Jacquesson, Hans-Jorg Mettig, Marco Vedovato, recently joined by Jose Luis Pereira); by Shinji Mizumoto and Kuniaki Horikawa of the ALPO-Japan and Oriental Astronomical Association; and by the JunoCam team (Candy Hansen, Glenn Orton, Gerald Eichstadt, Tom Momary, Mike Caplinger).

Global maps

Much use is made here of cylindrical maps of the planet, which are made regularly by members of the JUPOS team: principally Marco Vedovato, lately also Rob Bullen, and some also by Michel Jacquesson. Some maps have also been produced by Joaquin Camarena, and by several observers from their own images. Even more frequent maps are made by Shinji Mizumoto and posted on the ALPO-Japan web site: [*new URL:* http://alpo-j.sakura.ne.jp/indexE.htm].

Report no.7 presented a whole-planet map from 2019 July 19-20. Here we show further maps from July, August and September (Figure 2). In Figure 3, sectors of maps are aligned to show circumglobal changes from early 2018 to late 2019. They include fading of the NTB(S) and the northern fringe of the NEB and the northern half of the SEB (although note that the appearances of some belts varied with longitude). Most notable is the orange coloration of the EZ.

Zonal wind profile (ZWP) from Hubble data

Report no.4 presented a ZWP made by Marco Vedovato from amateur images in April. He has also produced one from the Hubble OPAL images on June 26-27 (Figure 4).
Sector 1: L3 = 205-305 (p. GRS)
Sector 2: L3 = 130-240 (further p. inc. oval BA)
The new ZWP shows good agreement with the April ground-based ZWP in the prograding range, but for all the retrograding jets, the April ground-based profile was blunted, the retrograding speeds being less extreme or zero. Thus the ground-based profile was similar to the zonal drift profiles that we routinely obtain by tracking of small spots, whereas the HST profile is more sensitive to true wind speeds.

Peak speeds of the major jets in the HST profile are as follows:

--NTBs jet: u_3 = 150 (±2) m/s (DL1 = -116 (±4) deg/mth). This confirms that the jet is in an intermediate state in preparation for another great outbreak (see below).

--NEBs jet: u_3 = 103 to 113 m/s (DL1 = +5 to -16 deg/mth). This matches the range of speeds that we observe for visible dark formations, large and small (see below).

--SEBn jet: u_3 = 142 (±2) m/s (DL1 = -76 (±4) deg/mth).

--SEBs jet: Sector 1: u_3 = -62 (±2) m/s (DL2 = +128 (±4) deg/mth):

Sector 2: u_3 ~ -57 & -43 m/s (DL2 ~ +117 & +86 deg/mth).

Within the uncertainties, DL2 = +128 is a typical peak speed for this jet; +117 is the speed of the most rapidly retrograding SEBs rings (see below); and +86 is the speed expected for the SEBs wave-trains as observed by JunoCam (see PJ23 report). More precisely, our relationship between wavelength and phase speed [Rogers et al., 2016, Icarus] predicts DL2 = +87 for the observed wavelength of 4.5° (equal to the fastest, shortest wave-train that we reported, observed in 2015), and +89 for the observed wavelength of 4.2°.

Both sectors included the S.Tropical Band, visibly disturbed at the time, but there was no perturbation of the ZWP there.

High northern domains

Figure 5 shows north polar projection maps from JunoCam at PJ20 (May 29) and PJ21 (July 21) and from amateur images in the intervening period. On May 28-29, the best part of the ground-based map shows some features validated in the JunoCam map up to ~72°N (70°N planeto-centric). There are many FFRs (cyclonic folded filamentary regions) and some AWOs (anticyclonic white ovals). One FFR at ~72°N (a light patch at L3 ~ 290) can be tracked through the maps of June 3-5 and June 9-11, as can various small dark spots and streaks at somewhat lower latitudes in the N5 and N4 domains, as shown by blinking the maps. These features are not clearly recognisable across the longer interval to the map of June 26-27, although one can identify small AWOs (also tracked by the JUPOS measurements). Thus, the best amateur images may allow tracking of small features in the hitherto inaccessible north polar regions, over intervals of 1-2 weeks, although one has to take account of projection inaccuracies and limb-parallel artefacts in such maps.

N5 domain

There has been just one conspicuous feature, a large AWO near 60°N. It was tracked from March to Sep. with fairly steady retrograding drift, DL2 changing gradually from +15 to +9 deg/mth. (See Juno PJ20 and PJ23 for views of it.)

N4 domain

The JUPOS chart (lat.+48/+52°N; not shown here) shows various minor features, all with DL2 = +6 (±0.5) deg/mth.

N3 domain

The JUPOS chart (lat.+45/+48°N; not shown here) shows about 9 well-tracked spots, both dark and bright, lasting from ~3 weeks to ~6 months, mostly with DL2 ~ -22 deg/mth, though with a range from -15 to -27.

N2 domain

[See JUPOS chart in Supplement, & Figure 6]

Five anticyclonic ovals in the NNTZ have been well tracked (see the JUPOS chart & Figure 6). Although I still call some LRS (Little Red Spot) and others WS (White Spot), the distinction between them is imprecise this year. LRS-1 has hitherto been the largest, but now WS-4 is equally large and at least as red (see the HST map in Figure 6); in future it should probably be called LRS-4.

LRS-1: This has been optically invisible for most of the year, having no contrast with its surroundings, but has occasionally been recorded as more reddish from June to Oct. It is still very bright in methane images, which enabled it to be tracked. It has been irregularly prograding in L2.

WS-4 (LRS-4): This large, methane-bright oval was bright white early in the year, but then variable in brightness, and latterly reddish. (It was clearly reddish in the Hubble maps (June 26) and JunoCam images (PJ23).) For most of the year it was almost stationary at L2 ~ 130.

LRS (new): A small bright reddish oval. (JunoCam recorded it at PJ21.) It was rapidly prograding until it encountered a tiny, dark-rimmed ring p. it in late August, and they possibly merged. [Aug.21 (Miyazaki/Barry), 22 (Foster), 24 [lower res.], 26 (Miyazaki); then only the dark patch around the ring was visible; on Aug.31 (MacNeill), there was a single bright, slightly reddish-white spot]. This was an example of prominent AWO decelerating on encountering an apparently minor slower spot.

WS-6: Bright white, weakly methane-bright, irregularly prograding in L2. Also:

WS (new): Bright white, small, irregularly prograding in L2 until it was 17° f. WS-6 in Sep. (The pair were well imaged by JunoCam at PJ22 [Sep.12].) In Oct-Nov. it accelerated further towards WS-6 and on Nov.5 (Wesley) they were in contact, apparently about to merge; on Nov.10 (Foster) only one AWO was seen.

Segments of NNTB: Report no.4 mentioned that two dark segments of NNTB faded away in April. Another one (at L2~90-105) reddened then faded away in Sep. There were also longer but variable dark segments of NNTB both p. and f. NN-WS-6.
The one f. WS-6 (L2 ~ 50-80, L3 ~ 20-40) was illustrated and described in my PJ20 report (excerpt below). The one p. WS-6 had its p. end at L2 ~ 280 --> 260, L3 ~ 230 (Feb. to June), and its f. end at a FFR adjacent to WS-6. Because of its indistinct boundaries it was not tracked after June, but it still existed, being imaged at PJ21 (expanded account below), and eventually grew longer and darker.

<u>from PJ20 report:</u> "West of [the FFR] is a curious sector that looks like a dark NNTB segment being invaded by white clouds, both diffuse and sharp-edged; these include a brilliant white outbreak like in the FFR. Indeed, ground-based maps (Figure 9) show that this was a dark sector of NNTB that began to 'break up' within days of the PJ20 fly-over, going on to form a row of dark spots."

<u>from PJ21 report [expanded]:</u> "NN-WS-6 was viewed, though obliquely. [Better closeups of two other long-lived AWOs in this zone have already been obtained at several perijoves: NN-WS-4 (PJ1, PJ12) and NN-LRS-1 (PJ3, PJ7, PJ14).] Also, the hemispheric maps reveal a new anticyclonic 'Little Red Spot' in the NNTZ. This has been tracked as an AWO by JUPOS since March, but here it is distinctly reddish and methane-bright. [NN-WS-6 and the new LRS were imaged again at PJ22.] Most of the sector viewed consists of a rather turbulent brown segment of NNTB whose f. end is overridden by a spectacular FFR, showing many of the beautiful features described in earlier perijove reports. This in turn abuts NN-WS-6." [The JunoCam map is consistent with our ground-based maps, which suggest that this whole sector has been unstable for the last several months, with varying proportions of FFR and dark NNTB, although the details were difficult to resolve. In April, when there was apparently no FFR there, JUPOS charts showed that WS-6 was prograding rapidly in L2, but thereafter it decelerated, consistent with our hypothesis that interaction with FFRs sometimes prevents these ovals from prograding.]

The JUPOS chart reveals several retrograding dark spots in the N2 domain, and the most rapidly retrograding feature (DL2 = +15 deg/mth) was a dark projection on NNTBn.

NNTBs jetstream (N2 jet):

The outbreak of dark spots was still proceeding; they were present at most longitudes. Most had DL2 ~ -81 (±2) deg/mth.

N1 (N. Temperate) domain

[See JUPOS chart & Figure 6.]

Most of the NTB is very pale. But the disturbed sectors persist: throughout 2019 (Feb-Nov.), the maps showed the *NTB rifted sector* (green line in Figure 6; see JunoCam at PJ18), and tens of degrees f. it, the *N. Temperate Disturbance* (NTD; green arrow; see JunoCam at PJ20 [text below] & PJ23). The NTD usually had a distinct f. end with DL2 = +23 deg/mth (May-Aug.). Also, from June to Sep., there was a small, very dark reddish-brown 'barge' just p. the rifted region, with mean DL2 = +12 (JunoCam closeups at PJ21 and PJ22, along with two similar but low-contrast cyclonic cells). It was fading in late Sep. All these features moved with the usual slow current, the retrograding N. Temperate Current A (NTC-A).

<u>from PJ20 report:</u> "For the first time, JunoCam captured an image of the *North Temperate Disturbance (NTD)*, a darkened sector of NTZ that appears f. (west of) a rifted sector of the NTB. There has been such a rifted sector with a NTD since early 2018, but the NTD had faded recently so I had not predicted the opportunity for PJ20. Nevertheless, the NTD has revived (Figure 9) and was imaged (Figure 8), along with some bright rifts emanating from the f. end of the rifted region. The NTZ does appear more thoroughly disturbed, on a small scale, than at many previous perijoves, but a proper comparison remains to be done. The NTD darkening appears to be due to diffuse streaks or patches of dark grey and reddish material – again, quite possibly grey aerosols rather than cloud clearing."

There was a narrow dark NTB component at 28°N for a variable distance p. the rifted sector. But there were only occasional dark spots prograding in this latitude from the rifted sector in the NTC-B, usually in pairs.

NTBs jet:

Although the NTB(S) is very faint, blinking of image pairs 20 hours apart revealed several tiny dark spots moving very fast within its pale, orangey south edge. Specifically:

May 23-24 (Foster, MacNeill, Olivetti): one spot moving -6.1° in 39.5 hrs, DL1= -3.7 deg/day;
May 24-25 (Olivetti, MacNeill): 3 spots moving -3.1° to -3.8° in 19.9 hrs, DL1= -4.2 deg/day;
June 5 (Soares, Foster; ***Figure 1***): 2 spots moving -2.8° in 19.9 hrs, DL1= -3.4 deg/day.
Mean DL1 = -113 (±13) deg/mth, u_3 = 148 (±6) m/s, at 23.8 (±0.2) °N.

This agrees well with peak jet speeds shown in Marco Vedovato's ZWPs, both ground-based in April (Report no.4) and Hubble-based in June (see above, Figure 4). All these are plotted on our long-term chart of NTBs jet speed in Figure 7). These speeds are intermediate between 'fast' speeds, shown by vortices in the 1990s, and 'super-fast' speeds shown by white spots in NTBs jet outbreaks, but still not as high as observed within one year before previous outbreaks. Therefore, in line with the usual 5-year periodicity, we predict a new NTBs jet outbreak in 2021.

N. Tropical domain

[See JUPOS chart, & Figure 3]

The NTropZ is now all white, as the residual yellowish colour from the previously expanded NEBn had essentially disappeared by August. White Spot Z (WSZ) had DL2 = -6 (±1) deg/mth for most of the year but DL2 = -11 in July-August. Juno flew over it at PJ21 and produced the best images of it so far, albeit obliquely. Several other AWOs or bays in NEBn have persisted through most or all of 2019, and there have been many shorter-lived ones; but there were only a few barges, which have not persisted. The NEBn edge is irregular.

The NEB has not changed much during the apparition, being a dark brown belt of normal width, with no major rifts (although the JUPOS chart for mid-NEB, 10-14°N, shows several long-lived tracks of white spots or streaks with DL2 ~ -125 deg/mth). Images occasionally showed a tiny bright spot in the southern part of the NEB but these did not become prominent. However, in late November, a large rift was observed. On the NEBs, a regular array of typical large dark formations was prominent.

In the methane band, large-scale waves were not detected this year.

Equatorial Region

NEBs:
There have been 10-11 major NEBs dark formations throughout most of 2019, with fairly steady DL1 in the range ~ +2 to +7, averaging +5 deg/mth. There were also some short tracks of features with faster drifts, e.g. DL1 ~ -20 deg/mth.

EZ:
The strong ochre colour of the EZ was the most impressive feature of this apparition. This was the most substantial EZ coloration episode since 1990-91. Figure 3 shows the timecourse. It had begun in spring, 2018, and continued to intensify up to solar conjunction. It was most intense for the first six months of 2019. Since the summer, images suggest that the colour has gradually been fading (becoming lighter). Niall MacNeill commented on his images on Sep.1: "The sandy colour of the EZ seems to be both diminishing in intensity, and north of the SEB, the region has turned white, like a curtain being raised. Perhaps the zone is in the throes of returning to its more usual white colour? Ethan Chappel recently showed me some images where the EZ is distinctly whiter around the dark blue/green festoons in the north part of the zone near the NEB."
These impressions have been reinforced as the autumn progressed. However, this is a subjective impression and not all observers are sure of it. Clyde Foster cautions that diminishing resolution, and variations in image processing, make a rigorous assessment difficult.

S. Tropical domain

SEB: [See JUPOS chart]
The SEB has not changed significantly since our Report no.4 in May. As stated therein: "The SEB still consists of three fairly narrow dark components: SEB(N) at 9°S, SEB(C) at 13°S (absent for some distance f. the GRS), and SEB(S) at 18-19°S (broad and disturbed f. the GRS, narrow and dark p. the GRS). The broad white 'SEB Zone' f. the GRS is still prominent. Indeed, we have the strange situation in which the northern half of the belt is largely quiet and whitened, while the southern half shows normal activity of the post-GRS rifting and SEBs jetstream spots. In the past, intense EZ coloration events have often been associated with SEB Fades, so I speculate that the paleness of the northern half is a compensatory response to the EZ coloration, but it has not (yet?) developed to a Fade encompassing the whole belt."

Figure 10 shows the first appearance of one of the bright plumes f. the GRS, and how it rapidly expanded to form a rift.

There are now two white lozenges or 'white barges' in southern SEB, both probably derived from earlier brown barges [see JUPOS chart]. As of Oct.10, they were near L2 ~ 200 and 250, both with DL2 = +5. One was viewed close-up by JunoCam at PJ23.

SEBs jet & rings:
The JUPOS chart for 2019 shows about 30 good tracks for retrograding SEBs jet spots (rings, anticyclonic vortices), with DL2 ranging up to +120 deg/mth. Those that approached the GRS

are also shown on the chart by Shinji Mizumoto (Figure 8A). Many of them decelerated as they approached the GRS, to different extents. This outbreak was still continuing in November. Also, in June-July, JUPOS recorded a pair of rapidly retrograding tracks at lower latitude inside SEB(S).

Short-wavelength waves on SEBs, similar to those we reported in previous years [Rogers et al., 2016, Icarus], were seen in many hi-res images near opposition, and in JunoCam images at PJ23; see ZWP section above. One such wave-train can be seen passing oval BA in Figure 14 (Aug.22). The animation in Figure 1 shows the motion of these waves, retrograding less rapidly than the rings just south of them.

The JUPOS charts also show tracks for some tiny white spots retrograding within the SEB(S) at ~18-19°S. One pair was well tracked, with DL2 = +100 to +110, passing both white barges; then they suddenly decelerated to DL2 ~ +85 (±4). Other tracks with DL2 around +90 were very short, at L2 ~ 140-190, i.e. they terminated in reaching the first white barge.

GRS & flakes:

A remarkable phenomenon in 2019 was the repeated emergence of 'flakes' of red, methane-bright material from the GRS, typically induced at its f.(W) end several days after a retrograding SEBs ring had entered the Red Spot Hollow (RSH) at the p.(E) end. These phenomena were described in our previous reports up to no.7 (July 31), which was just after Juno flew over the GRS at PJ21. They have been fully documented in maps and charts prepared by S. Mizumoto (ALPO-Japan & OAA), posted on the ALPO-Japan web pages (*new URL*):
http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j19_Maps_Animation_GRS.htm
The final chart is in Figure 8A. The following account is mostly derived from those maps and charts, and a comprehensive account is in preparation.

Up to late July, the last flake emerged from the p. end of the GRS on July 19 and was imaged by JunoCam two days later at PJ21 (Figure 9). From then on, there were no further rings on the SEBs for a long distance, and indeed no more flakes were produced from the GRS until September. In August (Figure 10) the GRS was a symmetrical red oval, with a light brown collar around it, and it recovered somewhat in length (see below).

No further SEBs rings arrived at the RSH until early Sept. (Figure 8A). [A smaller spot arrived on Aug.20 but had already almost disappeared and had no effect.] Then, a series of 7 of them arrived from Sep.8 to Oct.17, and each one apparently led to a flake (albeit small) appearing at the f. end 3-6 days later. The first was recorded on Sep.13. In most cases the SEBs ring and/or brown material associated with it (probably including the incipient flake) could be tracked around the RSH to the f. end, where it formed a brown or reddish-brown bridge to the SEB(S) which we list as a flake. (This happened even though the rift in the dark rim of the RSH (the 'chimney') was 'open' from Sep.10 to Oct.12.) However, at this late stage in the apparition there was insufficient resolution to distinguish how much of the feature came from the GRS. There was also evidence for flake material extending westwards along the SEB(S) f. the GRS during this period, in the form of an irregular dark red-brown streak that formed in later Sep. and grew longer up to Oct.23, when it extended 45 deg.long. from the f. end of the GRS.

Examples are in Figure 11A, which shows two successive flakes at the f. end, the lengthening reddish streak along SEB(S) f. GRS, and a protrusion at the p. end of GRS – as well as the f. end of the STB Spectre passing the GRS.

Also, from Sep.21 onwards, small protrusions from the p. end of the GRS were often observed. As before, it is likely that these were flake material that had travelled round the S side from the f. end, although the resolution was now too low to visualise the transfer. Overall, the phenomena in Sep.-Oct. were all consistent with the 7 SEBs rings inducing flakes in the same way that we recorded earlier in the year.

The aftermath was nicely imaged by JunoCam at PJ23 (Nov.3) (Figure 11B): the map showed the GRS surrounded by red, methane-bright loops, probably representing two or more of these flakes now wrapped around the GRS. A white spot in the RSH may have been a recently entered SEBs ring [no.24].

Measurements of GRS length were done by the JUPOS team and by K. Horikawa and S. Mizumoto (ALPO-Japan: Figure 8B). With the major flaking events in April-May, it shrank dramatically, and from late May to early July it was exceptionally small, averaging 12.1 deg long. It then recovered somewhat and was about 13.5 deg.long in Aug. & Sep., and 14.0 deg. long in late Oct.—almost back to its length at the start of the year.

The GRS mean drift rate throughout 2019 has been DL2 = +1.9 deg/mth, with the 90-day oscillation superimposed as usual (Figure 12). It was not affected by the flaking events.

S. Tropical Band (STropB):

Again, this account is largely derived from the maps and charts posted by S. Mizumoto on the ALPO-Japan web pages (*new URL*):
http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j19_Maps_Animation_GRS.htm
--and much more detail can be seen in those maps.

Two dark rings were prograding p. the GRS at ~24°S, presumably both anticyclonic, associated with the S.Tropical Band at ~25°S (Figure 8A & Figures 13-15]).

No.1 formed in May-June: the disturbances around the GRS in late May had produced a turbulent mixture of dark grey STropB, extended red flake, and eddies, all prograding p. the GRS, from which two coherent methane-bright rings developed on the STropB north edge, and they merged on June 23 to form Ring no.1. Its mean drift rate was DL2 ~ -50 deg/mth (from June 8 to July 25), on which date it came alongside the f. end of the dark STB segment and suddenly decelerated to -7 deg/mth (July 25—Sep.30). Then it accelerated again.

No.2/3 was the product of two retrograding SEBs rings that recirculated just before reaching the GRS in July: each one drifted south and reversed its drift, then they merged, creating this prograding Ring no.2/3 in the STropB (Figure 9, PJ21). [The process was similar to the origin of a S.Tropical Disturbance in the Voyager 2 approach images, but this year it did not proceed to form a STropD.] Its mean drift rate was DL2 ~ -28 deg/mth (July 21—Sep.24), oscillating, then decelerated to ~-10 deg/mth.

As the STropB faded, both rings were left almost isolated in the southern STropZ. Both were tracked until late October, and were shown in closeup images at PJ23 (Nov.3).

The dark grey-brown STropB at ~25°S had formed in April, from dark material streaming eastwards around the S edge of the GRS, and it continued to elongate rapidly, with an imperceptibly tapered p. end, which then combined with the dark STB(N) p. oval BA to produce a band that extended almost completely around the planet in July. But it also began to decline in July, with the (temporary) end to SEBs rings retrograding into the RSH and generating red flakes, the fading of the GRS dark collar to light brown (thus, it would appear, cutting off the supply of dark material for the STropB), and the recirculation of the next two SEBs rings to create STropB Ring no.2/3 (which approximately marked the f. end of the STropB). The STropB then rapidly faded away in August, although the STB(N) p. oval BA remained dark until September.

S. Temperate (S1) domain

[See JUPOS chart, & strip-maps from amateur data (Figure 13) & from JunoCam (Figure 17).]

Oval BA & dark segment f. it:

Ovall BA and the region around it have changed little during 2019 (Figures 13-17). BA is white, with a narrow dark rim. (It was viewed by JunoCam obliquely at PJ19.) There is a short dark turbulent segment of STB f. it, which presumably generates the dark rim around BA, the dark spotty STB(N) p. it, and the dark spotty 'tail' Sf. it. BA had a sudden severe deceleration at the end of March, and since then has had some fluctuations in speed, but has average DL2 = -14.2 deg/mth, still in the fast range (Figure 16). This accords with the persistence of the turbulent segment f. it.

That turbulent segment of STB remained ~20-22° long from March to Sep., not showing its expected shrinkage. Sf. it there is a variable dark 'tail', largely consisting of a narrow dark band in the STZ. The f. end of this band repeatedly remained roughly stationary in L2 for several weeks (including, in May, when it was due S of the GRS). One small AWO (methane-bright, with dark rim) was embedded in the STZ Band and was well tracked since Feb. (and probably since 2018); on April 1 it merged with another one (Report no.4). A second small AWO was well tracked from May onwards – rimless in early May, then acquiring a dark rim, near the irregular p. end of the STZ Band. The likely merger of these two AWOs, in association with the p. end of the STB Spectre, is described below.

The STB Spectre:

This cyclonic circulation is still extremely long. The *f. end* has been fairly distinct since April, in hi-res images. It was closely imaged by Juno at PJ21 (July 21) (Figure 9), and passed the GRS in October (Figure 11).

The p. end of the Spectre was very difficult to define for most of the apparition: it had no perceptible contrast, it was confounded by adjacent dark patches in the STropB and STZ, and it was often not distinct in methane images either (although the Spectre as a whole was still darker in methane). However, the p. end could be located clearly in the HST images on June 26-27 (Figure 9) and the JunoCam map on Nov.3 (PJ23). Methane-band and spacecraft positions for it are superimposed on the JUPOS chart. It seems to have maintained a very rapid average drift rate (DL2 ~ -21 deg/mth, but to have been repeatedly associated with features in the STZ marking the f. end of the 'tail' Sf. the STB segment f. oval BA.

One of these, a small AWO that it probably encountered in July, accelerated to the same speed as the Spectre p. end, until it encountered the other small AWO p. it in Sep. (Figure 15). Both AWOs are indicated by red arrows in Figure 15; the p. one was tiny but embedded in a substantial, very dark spot. The f. one may be visible on the S edge of this dark spot on Sep.17, and they were probably merging on Sep.20. The merged AWO was closely imaged by Juno at PJ23 (Nov.3); it then marked the f. end of the dark STZ 'tail' and was adjacent to the p. end of the STB Spectre. Figure 15 also shows pair(s) of small white ovals in the STZ 'tail' (cyan arrows); these were probably cyclonic features moving more slowly than the AWOs, consistent with their invisibility in the methane image.

At PJ23 (Nov.3), the Spectre was 110° long!

There is still no third structured sector. Small faint grey streaks across the whitened STB (Figure 13), shown to be cyclonic eddies in the PJ19 images, still exist but have not become prominent.

S2 domain

[See JUPOS chart, & strip-maps from JunoCam (Figure 17) and from amateur data (Figure 18).]

The most obvious features of this domain, as always, are the AWOs – currently 8 of them. This year they had DL2 ranging from -28 to -34 deg/mth (when steady over several months). A1 is the largest and A5a the smallest. A5a approached to within 10° of A7 in Sep., but rebounded and survived. [Since A6 and A7 merged, Marco Vedovato has called the resulting oval A6, whereas I am calling it A7, in case A5a ever grows large enough to deserve redesignation as A6.]

In the intervals between the AWOs, as usual there were a variety of cyclonic structures: white oblongs, dark bars, and FFRs.

Two intervals had white oblongs, which had persisted from 2018: the A8-A1 and A1-A2 intervals. A8-A1 was a white oblong 23° long in Jan., elongating as the AWOs moved apart. In Feb. it became duller, and up to Oct. it remained dull white, while the ovals moved to a maximum of 80° apart in Sep. In June, a dark strip of 'southerly SSTB' developed as a tapered 'tail' f. A8, becoming a distinct dark segment of (S)SSTB, elongating (f. end DL2 = -17, July—Oct.) until it covered almost all the southern half of this sector, while the north half remained dull white. Images by Hubble (June 26-27) and JunoCam (PJ21, July 21) clearly showed the braided border of the narrow white strip. A1-A2 was a bright white oblong from Feb. to the end of May. In June it elongated and became duller, so it was dull white up to Oct. (JunoCam viewed it closeup at PJ22 in Sep. and showed it was disturbed.)

The interval A7-A8 initially included two short dark bars. As the AWOs converged, in May these bars merged into one, 13° long, which was very dark brown from June to August. It faded in Aug. and disappeared in Sep.

FFRs can be seen in the best amateur images and maps, and more systematically in spacecraft maps from Juno and Hubble (Figure 17). They were present between A2-A3 (small and intermittent); p. A4 (intermittent); between A4-A5; p. A5a (see below); and between A5a-A7 (up to June, then this interval was less disturbed). Note that some transformed into less turbulent structures, for a shorter or longer time. The FFR p. A5a has existed for several years, sometimes 'feeding' this small AWO with smaller vortices but sometimes threatening to weaken it; this year it was in contact with the AWO; it was a FFR (though variable) up to early July, but thereafter it was absent (mid-July to Sep.) (Figure 15).

In the longer intervals between AWOs, lacking well-defined cyclonic structures, we tracked several slow-moving features. These were dark spots or streaks (i.e. (S)SSTB segments) at 40-41°S, the same latitude as the AWOs, diffuse and grey in spacecraft images – similar to the 'tail' commonly seen in the STZ Sf. S. Temperate structures, as described above. Such features were recorded f. A3 in Feb.-March, f. A5 in Feb.-April, and f. A8 in July-Oct.; plus a cyclonic white oval f. A5 in May-July. Typical speeds were from DL2 = -17 (the f. end of dark (S)SSTB f. A8) to -19.5 (the cyclonic white oval f. A5).

High southern domains

S3 jet:

Only one dark spot was tracked in this jet, for the month of April, with DL2 = -98 deg/mth.

S3 domain: [See JUPOS chart]

In recent years, by integrating modern hi-res amateur data with maps from Hubble and Juno, we have been able to define long-lived features and patterns in this domain which are similar to those of the S1 and N2 domains; it is more structured than other high-latitude domains. So I have repeated this exercise for 2019, although not showing the maps here. The JUPOS chart shows several white spots with diverse drifts lasting for ≥3 months, and several dark spots with retrograding drifts at various longitudes. By adding measurements of AWOs from the JunoCam and HST maps, it is possible to track four AWOs well during 2019, although they cannot be reliably tracked from 2018 because of their variable drifts.

S3-AWO-1, which is very long-lived, is identified as the largest of the white ovals. JunoCam positions suggest a steady drift of DL2 = -19 (±1) from late 2017 to early 2019, but this is only an average, as JUPOS records in each year show substantial irregular short-term variations in drift; and from 2019 Feb. to the end of May, the oval was near-stationary at L2 ~ 77. Then it accelerated again, and reached DL2 = -46 in Sep-Oct.

The JunoCam maps show that there were FFRs at various longitudes, although there was one sector which was notable as being largely or completely occupied by FFR(s) (L3 ~ 200-340 in late 2018, L3 ~ 230-320 throughout 2019; partly visible in maps in Figure 17). (L3 is useful in this domain as it happens to match the speed of the slow current, the S3TC). This was the same as the long-FFR sector in 2018.

Retrograding dark spots were tracked by JUPOS at various longitudes (DL2 = +8 for the best-tracked one, which is typical of the S3TC, but also one reaching DL2 = +18). Some were in 'tails' Sf. FFRs, others were on the S edge of the long FFR(s). One AWO (no.4 on the chart) also had similar speed, DL2 = +10 (May-Oct.). But unlike previous years, these retrograding dark spots were not restricted to any particular sector – consistent with the widespread distribution of FFRs which I believe generate the dark spots.

We have previously noted instances of a S3-AWO decelerating upon encountering seemingly minor retrograding spots, and there were more possible instances this year. At PJ18 in Feb., when S3-AWO-1 had apparently just halted, it abutted a Sf. tail of dark spots probably retrograding from the very long FFR, which may explain the halt (and at that time only, it had a dark rim in the JunoCam images). But when it was subsequently stationary, it was some distance from these spots as the FFR prograded in L2. Nevertheless, the JUPOS chart for 2019 shows that other S3-AWOs also tended to accelerate then suddenly halt, sometimes in proximity to retrograding dark spots.

S4 domain:

S4-LRS-1 was very well tracked, with DL2 varying between -16 and 0. Another AWO was tracked from March to June, rapidly prograding (DL2 ~ -27, variable), until around June 12 when it may have halted at L2=270, then soon disappeared.

South Polar Region

In the best south polar projection maps from amateur images, features can be detected up to ~75°S (all latitudes planetographic), and identified with AWOs and FFRs shown in JunoCam maps (e.g. Figure 19). In 2016, JUPOS measurements of amateur images tracked a white spot at 71°S, which turned out to be the largest in a loose ring of AWOs near that latitude as seen in the subsequent JunoCam PJ1 images. The JunoCam team have monitored these AWOs at every perijove since then. In 2019, JUPOS tracked four white spots in this latitude range (71-74°S). As seen in JunoCam map (e.g. Figure 19), two of the spots were relatively large AWOs tracked through several perijoves; one was a compact FFR; and the fourth track may have included a small AWO and a FFR. They were all retrograding with DL2 ranging from +10 to +18.5 deg/mth; from combining JunoCam and JUPOS data over the last 3 years, we know that this is the usual speed range for these latitudes. A report that combines the JUPOS and JunoCam results will be posted separately. The JUPOS results, analysed by Gianluigi Adamoli, were as follows.

spot	*time interval*	*L2(0)*	*ΔL2(°/30d)*	*U3(m/s)*	*Lat.*		*N*
					graphic	*+/-*	
AWOs							
W1	Feb 24 – Apr 16	154,4	10,0	-2,8	-71,3	0,4	12
	Jun 19 – Jul 16	151,0	18,5	-3,7	-74,1	0,8	7
W2	Feb 15 – Apr 8	243,4	12,7	-3,2	-72,6	0,6	12
W3	May 12 – Jul 9	300,7	16,1	-3,9	-72,0	1,4	8
FFR							
	Apr 27 – Jul 22	268,5	14,1	-3,6	-71,1	0,8	18

Impact flash

On 2019 August 7, 04:07 UT, amateur astronomer Ethan Chappel from Cibolo, Texas, USA, observed a fireball on Jupiter, representing the impact of a small asteroid or comet. Chappel recorded his video in the red channel with a Celestron-8, Chroma Red filter and ASI 290MM. The flash was recorded at approx. L2 = 23, 18.4°S, in the southern SEB. No impact scar was observed in images over the following days.

This was the sixth such impact detected. The first was on 2010 June 3, and the fifth was on 2017 May 26.

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Appendix: **Towards a new three-year weather forecast for Jupiter** [as of 2019 Sep.]:

Our improved understanding of Jupiter's large-scale climatic cycles now enables predictions for some phenomena and possibilities for others. In early 2015 I ventured a three-year forecast, and the predictions therein were largely fulfilled, although with significant differences in timescales. This success was largely because there were indications that several large-scale cycles were beginning at that time. In 2019 this is not the case so it is more difficult to make predictions. Nevertheless, at the EPSC in Geneva in 2019 Sep. I presented the following thoughts.

The NTB: A new NTBs jet outbreak is likely because (i) they typically recur at 5-year intervals; (ii) the NTB is now faded; (iii) the jet has recovered to an intermediate speed. Therefore, I expect a new NTBs jet outbreak in 2021.

The NEB is in a fairly normal state which could last for some years, or a new cycle of broadening to the north could start any time from 2020 onwards. These 'NEB expansion events' typically occur every 3-5 years; the most recent occurred in 2017. The belt has now retreated again. A new expansion event could begin in the next 2 years, or the series may have finished.

The EZ coloration event is the most intense since 1989-91. Previous intense episodes like this one have lasted between ~2.5 and 5 years. This episode began in spring, 2018; is maximal in 2019; and may now be starting to fade. So it is likely to continue at least into 2020, but it could terminate any time in the next few years.

The SEB is in an unusual state with the north half largely whitened but the south half showing normal convective and jet activity, so prediction is uncertain. The last SEB Fade/Revival cycle was in 2010. The belt does not appear to be entering a fully inactive and faded state, but it could do so with only a few months warning. Even if not, a mid-SEB outbreak could erupt any time and would be much the same as a SEB Revival.

The STB: There are presently just two STB structured sectors: the STB Spectre and the complex around oval BA. The Spectre is very elongated & low-contrast; it will catch up with the dark segment f. oval BA in 2020, and may transform turbulently into a dark STB segment as the STB Ghost did in 2018, but given its exceptional length, it might behave differently. A new structured sector is expected to form soon, probably tens of degrees p. oval BA.

Figures

Figure 1. Animated blink pair of images taken on 2019 June 5, 20 hours apart, centred on oval BA: it is a beautiful display of the jovian currents.

Figure 2. Three global maps_2019 July 8-11, Aug.8-9, Sep.23-25. For labelling of features, see the sets of regional maps in subsequent figures.

Figure 3. Sectors of maps are aligned to show circumglobal changes from early 2018 to late 2019.

Figure 4. Zonal wind profile made by Marco Vedovato from Hubble OPAL images on June 26-27. The images were obtained by the OPAL project (Credit: NASA, ESA, STScI, Amy Simon & Mike Wong & Glenn Orton. Christopher Go assisted with image processing.). Link and reference for Vedovato's ZWP and maps: http://pianeti.uai.it/index.php/Jupiter:_ZWP_and_maps_from_HST_2019_June_26-27

Figure 5. North polar projection maps from JunoCam at PJ20 (May 29) and PJ21 (July 21) and from amateur images in the intervening period. All are plotted in L3 with L3=0 to the left. The JunoCam maps were posted in my reports on PJ20 and PJ21; their latitudes are planetocentric. The JunoCam and amateur maps are on different projections. Ganymede happened to be in transit on two of the contributing images, 4 weeks apart, and appears in distorted form on the maps.

Figure 6. Set of maps of the N2 and N1 domains from 2019 April to Sep. Maps are aligned in L3, with north up. (Also see the labelled JUPOS charts in the **Supplement**, with maps aligned in L2 and south up.)

Figure 7. Chart of NTBs jet speed from 1995 to 2019, extended from versions in previous reports. The panel at right gives the sources of the last 4 values, including the mean of measurements given in this report. Note that after each super-fast (NTC-D) white spot outbreak, the speed falls back close to the NTC-C range, then accelerates again irregularly over subsequent years, leading up to the next NTC-D white spot outbreak.

Figure 8. Charts of the GRS and vicinity in 2019, by Shinji Mizumoto (ALPO-Japan). (JUPOS charts agree well with these charts but do not include the 'flakes'.)
(A) Chart of longitude (L2) vs time (yy/mm/dd) for spots interacting with the GRS, whose p. and f. ends are shown. The chart is oriented to align with maps with south up, opposite to the maps in this report. Grey: Retrograding SEBs jet spots (rings). Red: Flakes emerging from the GRS. Blue: Prograding rings that formed on the S.Tropical Band. All of these are numbered. 'RS bay rift' is the intermittent white rift in SEB(N) due N of the GRS.
(B) Length of the GRS.

Figure 9. The GRS region in cylindrical maps from Hubble (June 26) and Juno (PJ21, July 21). Red arrow indicates flake material recently emerged from the p. end of the GRS. The STB Spectre is alongside the S side of the GRS.

Figure 10. Images of the GRS region, August 1-8, in RGB (left) and CH4 (right). They show the first appearance of one of the bright plumes in the SEB, which rapidly expanded to form a rift. At this time there were no SEBs rings nor flakes near the GRS.

Figure 11. The GRS region in cylindrical maps, with north up. **(A)** From amateur images, Oct.11-17; excerpt from the long series of maps by Shinji Mizumoto (ALPO-Japan).
(B) From JunoCam at PJ23, Nov.3: RGB & CH4. Streamers derived from flakes are wrapped completely round the outside of the GRS. The f. end of the STB Spectre is passing the GRS; note that the Spectre is dark in CH4.

Figure 12. JUPOS charts showing the drift of the GRS: (L) in L2, (R) in a system moving at -1.8 deg/mth in L2. The chart is oriented to align with maps with south up.

Figure 13. Set of strip-maps covering the STropZ and S. Temperate domain, L3 ~ 115-325, including oval BA and the dark features f. it. The STB Spectre is on the left-hand side though the limits are difficult to discern in these maps. All aligned in L3, with north up. See **Figure 17** for JunoCam maps.

Figure 14. Hi-res images of the southern hemisphere in August, including oval BA and the dark features f. it.

Figure 15. Set of images in Sep. showing oval BA and the dark features f. it, including the encounter of two small AWOs in the 'Sf. tail'. S2-AWOs are also labelled.

Figure 16. JUPOS chart showing the drift of oval BA over the past 3 years, in a longitude system moving at DL2 = -12.9 deg/mth. The chart is oriented to align with maps with south up, opposite to the maps in this report.

Figure 17. Set of strip-maps from JunoCam, covering the STropZ and S1 and S2 domains, aligned on the S2-AWOs (labelled A1 to A8). Scales are given in L3. To minimise discontinuities, 90 deg of each map is repeated.

Figure 18. Set of strip-maps from amateur images, covering the S2 domain, aligned in L3. These are excerpts from a larger set covering the whole apparition.

Figure 19. Examples of south polar projection maps. **(A)** From JunoCam at PJ20. **(B,C)** From amateur images. Arrows indicate bright spots (red, AWOs; green, an isolated FFR) that could be identified on multiple maps and tracked by JUPOS.