Jupiter in 2022/23, Report no.8:
Final report on the southern hemisphere

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This was an especially favourable apparition of Jupiter, with opposition on 2022 Sep.26. It had the closest opposition for 59 years past or 107 years future, as Jupiter would pass perihelion on 2023 Jan.21. Therefore, amateur observers obtained excellent coverage of the planet. This work depends essentially on their images, for the use of which we are very grateful. A list of the observers is posted on this web site and also on the JUPOS web site. This work also refers to JunoCam maps, due to NASA and the JunoCam team (Candy Hansen, Glenn Orton, Tom Momary, Gerald Eichstädt, & JHR), for which we are also very grateful. Further details of the JunoCam images are in our reports on each perijove, on this web site under 'Results from Juno (2022)'.

Events in the S. Tropical and S. Temperate domains were well covered in our previous 2022/23 Reports nos.2-5. Here we summarise those, and add JUPOS drift measurements plus latitudes as read off JUPOS maps. We have not done a full JUPOS analysis for these domains, for lack of time; ZDPs for them in previous years have generally been close to the zonal wind profile (ZWP) in most regions.

The higher-latitude domains are here described in some detail from JUPOS and JunoCam data, including a full JUPOS analysis for the S3 and S4 domains. This produces a zonal drift profile (ZDP) showing the drifts and latitudes of all the spots recorded. The last time we posted a complete set of ZDPs was for the 2015/16 apparition, and the present ZDPs for the S3 and S4 domains are much more detailed. The highlight is the measurement of group and phase velocities for a high-amplitude wave-train on the S4 jet.

Abbreviations and conventions are as in previous reports, unless otherwise specified. Circulations are anticyclonic white ovals (AWOs) and red ovals, and cyclonic folded filamentary regions (FFRs). P. = preceding (east), f. = following (west). Longitudes are plotted in L3 unless otherwise stated, but drift rates are generally given in L2 (DL2, deg/30d). DL3 = DL2 + 8.0 deg/30d. Latitudes are planetographic, except in the JunoCam maps where they are planetocentric. North is up in the figures unless otherwise stated.

As a reminder for readers, Figure 1 illustrates how the planet is partitioned into 'domains' separated by permanent eastward (prograde) jets, with the nomenclature that we use for them [refs. 1 & 2]. At low latitudes, each domain corresponds to the dark belt plus bright zone as visually defined when in their normal positions, but at higher latitudes, the correspondence becomes more uneven or absent. Dynamically, each domain is organised as follows (in order of increasing latitude): (i) the prograde jet that defines its boundary; (ii) a cyclonic 'belt', usually containing FFRs that drift with the zonal slow current (ZSC, named as for the domain: STropC, STC, SSTC, S3TC, S4TC); (iii) a retrograde jet (or velocity minimum) that sometimes carries small dark spots, possibly emitted from the FFRs; and (iv) an anticyclonic 'zone' containing AWO(s), which may drift with the ZSC, or in some cases faster eastward. While all domains have this pattern, they also show individual variations on it.

Figure 2 is a series of our maps of the southern hemisphere, one per month, mostly reproduced from our interim and/or perijove reports, with major features labelled on some maps. For examples of the highest-resolution images, see our Report no.4. Figure 3 is a series of maps from JunoCam, from the STropZ southwards, with dates of the perijoves (PJs), PJ41-PJ49. The later maps mostly have lower resolution, because some closeup images were lost, and thereafter the perijove track was on the night side; so the later maps were made from inbound and/or outbound images at increasing distance from the planet. Methane-band images and maps are not shown here but can be found in our Report no.4, and examples of methane-band maps from JunoCam are in our PJ47 and PJ49 reports.

SEBn jet

The SEBn edge, as usual, has no major features but numerous 'chevrons' at almost all longitudes. The flow of the SEBn jet was analysed in Report no.3 from June up to early Oct., and has continued unchanged since then (Figure 4). In Report no.3 the mean speed of the chevrons was given as DL1 = -36.1 (±6.1) deg/30d (N=16). From Oct. to Jan., the mean speed was not significantly different: -41.2 (±5.6) deg/30d (N=27). It is exceptionally slow for this jet, and not evidently related to the possible new S. Equatorial Disturbance (SED).

The possible SED is seen in the JUPOS chart as a vacant band (grey arrows in Figure 4) denoting a short gap in the chevrons, moving much more slowly then the chevrons: mean DL1 = +30 deg/30d. Maps from Nov. to Jan. (Figure 5) show that this strip of chevron-free SEBn, alongside clear white EZ(S), has a very small rift at its p. end, as it did earlier. It resembles the long-lived SED of 1999-2010 when it was in its quiescent phases. but it has not developed further during this apparition. [See Report no.3 for more information.]

South Tropical Domain

South Equatorial Belt (SEB)

The overall pattern of the SEB has not changed much for several years, nor during this apparition. The belt presents different aspects in three sectors, described here in relation to the GRS, which was at L2 = 14 (2022 April) --> 31 (2023 Jan-Feb.).

Following the GRS is the perennial rifted region. This year, it was short until 2022 August; intermittently more extensive and active in Aug-Sep. and again in Nov.; quieter again in late Sep. & Oct. In Dec. it quietened down again and in 2023 Jan. it was minimal.

F. the rifted region, up to L2 ~ 180, the SEB was light brown without major features but with small-scale turbulence. SEBs jet spots (see below) were arising ~80-100° f. the GRS (L2 ~ 100-130) from August onwards, athough they did not acquire their characteristic ring shape until further downstream, tens of degrees higher in longitude. Two red-brown barges began to develop in this sector in late 2022 and were distinct in 2023 Jan., at ~16.5°S, with DL2 ~ +4 deg/30d.

Further f., up to the GRS, the SEB consisted of 3 components (labelled in the Sep.29 map in Figure 2): the very dark SEB(S), irregular SEB(C), and narrow SEB(N) (which was partly disrupted by the SEBn chevrons).

The zone between SEB(C) and (N), spanning ~10-13°S, was often filled with a series of prograding irregular white spots. (JunoCam has shown that these often look anticyclonic, possibly because they have little vorticity in contrast to the surrounding cyclonic gradient: e.g. PJ45, Sep.29.) According to our Report no.3, they had mean DL2 = -85 (±6.5), and in 2021 they had mean DL2 = -93 (±9). In Sep-Oct., this zone also contained a distinct white strip (see Report no.3, esp. Fig.14), with DL2 = -109 for the p.end, -90 for the f. end. A similar white strip followed later in Oct-Nov., with DL2 = -91 for both ends.

SEBs jet

The JUPOS chart is not shown here but it is consistent with the detailed chart of the GRS region by Shinji Mizumoto (Figure 6).

There were very few retrograding rings in June or July, although one prominent one (no.6 on the chart) entered the Red Spot Hollow (RSH) on July 31 [Report no.3]. In August, three appeared (one probably being no.6 that had survived passing the GRS – see Figure 6). They reached the RSH on Sep.26, Oct.9, & Oct.24. From Sep. to Nov., there was much more activity: ten retrograding rings appeared, reaching the RSH from Nov. to Jan. In total, from mid-June to mid-Sep., only two such spots arrived at the RSH (0.7 per month), whereas from mid-Sep. to mid-Feb., there were 15 (3.0 per month).

Their speeds spanned the usual range. Spot no.6 (see above; June 24 to July 31) had DL2 = +94. Five spots in Sep-Nov. had mean DL2 = +130.8 (±4.1), very near the peak speed of the jet. Four subsequent spots, from late Oct. to Jan., had mean DL2 = +114.8 (±4.6), more typical for such rings.

Northern South Tropical Zone (STropZ)

In the first half of the apparition, while there were almost no rings on the SEBs jet, the northern STropZ contained a chain of amorphous dark grey patches and streaks at ~22°S. The more distinct ones lasted for 3-5 months, with DL2 ranging from +1 to +22 deg/30d (see JUPOS chart, Fig.7).

Also in the northern STropZ was a large ring, or dark-rimmed white AWO, which began at 21.7°S with DL2 = +37 (Aug.8 to Sep.1), then veered south to lie at 23°S (Sep.&Oct.) with DL2 = +9 (Oct.11 to Jan.4). So this AWO was initially in the shear region alongside the SEBs jet, then it drifted south to a latitude where persistent features drift with the S. Tropical Current. We nickname this ‘Spot Q’, as we have done for similar spots in earlier decades. It is marked with a green arrow on the maps (Figure 2).

Great Red Spot (GRS)

Motions of all features around the GRS are plotted in Figure 6, by Shinji Mizunoto. He also posted maps of the GRS region every 2-3 days from June onwards, which enable close study of these phenomena.

The GRS was at L2 = 14 (April) --> 31 (2023 Jan-Feb.). Its motion and length are shown in Figure 8. Its mean DL2 was +1.75 deg/30d throughout 2022, and in fact from 2021 Aug. to 2023 Feb. Meanwhile the ‘90-day oscillation’ (whose period has actually been 91.5 days for several years) continued like clockwork, and the rift or ‘chimney’ on the north edge of the RSH continued to appear and disappear in synchrony with it (Figure 8). The GRS shrank to its smallest ever size in June (11.5°), and has only fluctuated slightly since then between 11.5° and 12° (Figure 8). (JUPOS measures are usually ~0.5° longer.).

A few red flakes were observed inside the curve of the Hook, as in 2019. The more noticeable ones were already detailed in Reports nos.3 & 5, and one on Aug.3-6 (with aftermath on Aug.8-11) is shown again in Figure 9A. From Mizumoto’s maps, we can also record small flakes from Oct. to Dec. (**Table 1**). As in 2019 [refs.4 & 5], most of the flakes could be attributed to the entry of a retrograding SEBs ring into the RSH, which stripped red, methane-bright material off the periphery of the GRS a few days later as the remains of the ring were swept towards the f. end of the RSH [see Report no.3]. Sometimes the flake material then circulates round the S side of the GRS and emerges a few days later at the p. end.

This process accounted for most of the flakes observed, and in Aug.& Sep., when there were no incoming rings, there were usually no such disturbances to the rim of the GRS. Nevertheless, small flakes were still seen at the p. end of the GRS several times in Aug. and in Nov., of unknown origin; they could perhaps represent previous flake disturbances travelling multiple times around the GRS. (At PJ46 on Nov.6, JunoCam methane images showed two long narrow streaks indicating flakes being stretched out from the rotating GRS.)

Table 1. GRS flakes, 2022-23			
Ring enters RSH	*Flake at f.end*	*Flake at p.end*	*Ring enters RSH but no flake*
July 31	Aug.3-6f	Aug.8-11	
--	Aug.15	Aug.18 & 28	
(None for 8 weeks)			
Sep.26	Sep.30f	Oct.1f & 5-6	
Oct.9	Oct.13		Oct.23
Oct.29	Nov.2-4	Nov.6	Nov.3
Nov.8-9	Nov.11f (& 21)	Nov.11 & 14	Nov.12
Dec.3	Dec.8		Dec.8 & 14
Dec.28 & Jan.1	Jan.2-4		
Jan.8	(Jan.10-11?)	(Jan.13-14 & 19)	

Southern South Tropical Zone (STropZ) & Band (STropB)

The most prominent feature around the GRS was the dark ‘hook’ at its f. side that developed from the SEBs over June 26 to July 4 (Figure 2). As usual with such hooks, dark grey material rapidly extended in a collar around the S side of the GRS and began forming a S. Tropical Band (STropB) p. the GRS (July 8). Mizumoto has posted an animation of maps showing this process, in which detailed dynamical events can be seen: http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j22GRSanimL3n.htm . More details were given in Report no.3. Similar hooks had appeared most recently in 2019 April and 2021 Jan., and all somewhat resembled the S. Tropical Disturbance of 2018 as it streamed past the GRS.

From mid-July to mid-August the growing STropB, along with the adjacent STB Segment A, were a scene of dramatic turbulence (Fig.9A) – still evident in JunoCam closeups at PJ45, Sep.29. The STropB p. end advanced steadily with DL2 = -80 (mid-July to mid-Oct.) (see JUPOS chart of STBn in Figure 10). It extended all round the planet and arrived at the Hook again around Nov.11, at which time the Hook disappeared. This led to renewed intense disturbance p. the GRS in the second half of Nov.; then the STropB gradually faded away.

These events did not produce any change in GRS drift rate.

A small white oval or ring appeared on Aug.10 in association with a red flake emerging from the p. end of the GRS on the N edge of the ragged (very wavy) STropB, a location of intense disturbance (Fig.9A). This white spot prograded at 24°S with mean DL2 = -40 (Aug.11 to Nov.3). On Oct.1 it passed spot Q. In mid-Nov., it contracted to become a dark spot and then decelerated.

STBn jet

A massive outbreak of dark spots on the STBn jet was still in progress, emerging p. STB segment G (see below), as presented in Report no.3 and our PJ42 report, & Figure 10 (JUPOS chart). Speeds were all close to DL2 = -77 (±5). The maps suggest that the spots were drifting northwards as they prograded, as we have observed in previous outbreaks. As noted in our PJ42 report, they were emerging p. Segment G at 27.2°S or below (planetographic), but then mostly travelling at ~25.3°S. This is an unusually low latitude, north of the canonical STBn jet. (There was also such low-latitude disturbance including a few jet spots further f., alongside segment G and WS6, possibly emanating from STB segment A.)

Initially the STBn jet spots covered a large range of longitude, but they could not survive past the GRS (esp. not after the Hook developed; see the animation link above; & Figure 9B,C,D). So by Oct., as Segment G was drifting towards the GRS, they covered a much smaller range. Moreover, as the STropB extended around the planet, it replaced all the dark STBn jet spots in those longitudes [see Report no.4] – although the JUPOS chart shows that some could be tracked as bright spots for short distances, but not after late Oct. This sector was closely imaged by JunoCam at PJ46 (Nov.6), confirming that it contained a jumble of jet spots like the previous ones, but embedded in the dusky streaky STropB, thus indistinguishable in amateur images. However in late Dec., as the STropB faded away, dark STBn jet spots reappeared p. Segment G, with speeds similar to those recorded earlier. So it seems that the outbreak never actually stopped, but was temporarily obscured by the dark STropB.

South Temperate (S1) domain

This has already been covered in detail in Reports nos.2-5, so here we repeat the main features of these reports and bring them up to date.

The maps from mid-May onwards (Figures 2 & 3) revealed the evolution of all the features that attracted attention in 2021. There was now some kind of dark STB around half the planet; three segments of it were separated by major white ovals. In order of increasing longitude:

The p. part of the darkened sector was STB segment G (the descendent of Clyde's Spot/DS7): this was a well-defined turbulent sector, 30-35° long in June, 40-45° long in Oct.& Dec. (Juno viewed it well at PJ44.) Its f. end was close to cyclonic oval WS6. Around and f. WS6, there was a stretch of dusky STB as far as oval BA. F. oval BA, STB segment A had continued to lengthen so it was 80-85° long in June, but it remained ~80° long thereafter until Dec., when it expanded to ~90°. Its p. half appeared turbulent and its f. half plain and dark, but JunoCam maps showed all of it turbulent on different scales. Its f. end abutted the small STZ AWO.

Following segment A and this AWO there was a long dark 'Sf. tail' along the STBs jet and STZ. Its main part terminated at an even smaller AWO, adjacent to Spot 8, but it also extended even further f. in more tenuous and irregular form. Spot 8 (or DS8) was confirmed as a dark brown oval (& see PJ46).

Around the remaining longitudes, the STBn jet spots constituted a spotty STB(N).

The white ovals were a diverse collection, described as follows in Report no.3 (Oct.):

Oval BA (the large AWO) was off-white with a 'warm' tint, due to a slightly reddish internal annulus seen in v-hi-res images. It still had a modestly dark grey-brown rim. It was still drifting quite fast (see below), with variations over a matter of months. It was well viewed by Juno at PJ47.

WS6 (the cyclonic white oval) was generally 'cold' white (relatively bluish), but sometimes appeared to be resolved into different parts [see Report no.3 & PJ44 report for more details]. Although it was not methane-dark early in the apparition, it was so in late Nov. and Dec. [Fig.14, & Report no.5], until its demise as described below.

Between BA and WS6, a small dark spot in the STZ latitude (possibly the same as anticyclonic dark spot d1 in 2021 [2021-22 report no.10]) developed a bright centre in late May, turning into a small, dark-ringed AWO. Andy Casely tracked it and noted that in the methane band it was first visible by early July, grew brighter through August, and was notably methane-bright in Sep.& Oct. It remained strongly methane-bright in Nov.& Dec. [Fig.14, & Report no.5, Fig.4] and in JunoCam maps at PJ47 (Dec.15) & PJ49 (2023 March 1). The JUPOS chart shows it oscillating between BA and WS6 (also Figure 14).

The longer-established small AWO in the STZ was rimless and very bright white up to Sep. Curiously, it appeared bright in blue & UV light while not very bright in methane -- suggesting that its cloud cover had some similarity to cyclonic white ovals rather than to other AWOs. After Sep., it was not so bright. It was also not methane-bright in the JunoCam maps at PJ47 & PJ49.

A smaller white spot, always ~25° p. DS8, was shown to be a small bright cyclone in PJ43 and PJ46 images. Like DS8 and other cyclonic circulations, it was methane-dark. Around Dec.1 it was passing the GRS, and was very bright white, just like those which produced the convective outbreaks of Clyde's Spot in 2020 and Spot 8 in 2021 just after they had passed the GRS, but this one did not do likewise; it continued unchanged.

Several changes occurred from October onwards:

(i) During October, the broad dark STropB advanced across the sector p. STB Segment G, and obscured the STBn jet spots, as described above.

(ii) In Dec., as the STropB faded away p. Segment G, many distinct dark spots became visible again on the STBn jet.

(iii) F. Segment G, the cyclonic white oval WS6 became disrupted with dark spots inside, and appeared to merge with Segment G [Report no.5]. As first documented by Shinji Mizumoto, the transformation began gradually around Dec.12, and the white oval became darkened and chaotic. By Dec.28, IR and RGB images suggested that it had become part of the turbulent Segment G. However, it was still comparatively blue and strongly methane-dark. This appearance was sustained up to Jan.12, but by Feb. the merger was complete (Figure 14).

This was the first observation of a large cyclonic white oval being transformed and incorporated into an adjacent turbulent sector (although comparable to the transformations of the much larger STB Ghost in 2018). There was no methane-bright plume outbreak. WS6 may have been destabilised by its proximity to Segment G.

(iv) Spot 8 (or DS8) was a very dark brown cyclonic oval, well shown in the PJ46 images (Nov.6). But our PJ46 report suggested that it might redden and then whiten to form a cyclonic white oval, and this is what soon happened. It faded suddenly, just after it passed the GRS at the end of January, but the resolution was insufficient to show what happened to it. The JunoCam maps from PJ49 (2023 March 1; Figure 3) and PJ50 (2023 May 11) confirmed that it had become a light, slightly reddish oval flanked by blue-grey patches, just like previous examples of fading spots. Later its centre became white, but it was still very methane-dark. So it has evolved into a larger version of the small white cyclone that still persisted 27° p. it.

Drift rates:

Drift rates for the major features are now all quite similar and typical of the STC. They are summarised in **Table 2**. and shown in the JUPOS charts in Figure 11.

Oval BA's drift rate historically alternates between fast and slow ranges depending on the state of STB segment A, and in 2022/23 it was still in the fast range, segment A being turbulent. But it still oscillated irregularly between DL2 = -15.8 (which predominated from May to Oct. inclusive so the mean speed was -16.2) and -19.0 (which held from Nov. to Jan.).

WS6, DS8, and Segment G all had similar drift rates, although DS8 was slower from Oct. to Jan. The three small AWOs all oscillated, apparently being trapped by adjacent features, mostly cyclonic: one was between DS8 & WS9, one f. Segment A, and one between WS6 and oval BA. When the small AWOs were prograding most rapidly, they reached ~34°S (orange points on JUPOS chart), as they oscillated in latitude as well as in drift rate.

The JUPOS chart also shows some short retrograding tracks for small dark spots in STB segment A and its Sf. tail, affected by the retrograding jet. Drifts were (roughly) DL2 ~ +6 to +15, apart from two more strongly retrograding spots. One had DL2 = +23, Sf. segment G in June-July; the other had DL2 = +44, in the Sf. tail of segment A in August.

Table 2. South Temperate Current					
Mean drift rates (DL2, deg/30d) for major features in S. Temperate domain.					
Name	*Dates*	*DL2*	*L2(0)*	*L3(0)*	*Lat.(°S)*
Segment G, p.end	July-Oct.	-18	180	110	30-31
	Oct-Jan.	-17			
Segment G, f.end	May-Dec.	-16.7	215	145	30-31
WS6	April-June	-19.6			
	July-Dec.	-17.8	227	157	30
Oval BA	April-Nov.2	-16.2	268	198	33
	Nov.2-Feb.	-19.0			
Segment A, f.end	May-July	-13.8			
	Aug-Oct.	-17.5	350	280	30-31
	Oct-Feb.	-14.4			
Small w.cyclone	July-Sep.	-13.1	59	349	31
	Oct-Jan.	-16.6			
DS8	June-Oct.	-16.2	78	8	30.5
	Oct-Jan.	-12.5			
L2(O) = longitude at opposition, 2022 Sep.26.					
Drifts are averages, measured from JUPOS charts, ignoring smaller variations.					
Latitudes are measured from JUPOS maps.					

SSTBn (S2) jet

Only a few inconspicuous, short-lived dark spots were tracked in this jet. One in June had DL2 = -134. Another in Oct. had DL2 = -125. From Nov-Jan., a dark spot was tracked with DL2 = -55.

S.S. Temperate (S2) Domain

This domain is narrow, so the cyclonic and anticyclonic features differ only a little in latitude, and they typically all move with the same zonal slow current, the SSTC (Figure 12 = JUPOS chart; Figure 13 = JunoCam maps).

AWOs: There are still 7 large long-lived AWOs at ~40.6°S, numbered A1-A5, A7 & A8. AWO-2 had no rim and so was hard to detect in late-apparition ground-based images, but the PJ48 maps confirmed its continued existence. The 7 AWOs had mean speeds throughout the apparition ranging from DL2 = -27.8 to -31.8; over 2-month intervals the range was -26.9 to -36.0. The overall mean was -29.8 (±1.4; N=7).

There were two cyclonic white oblongs (CWOs), p. A5 and p. A2. Both were methane-dark (esp. in JunoCam maps). The CWO p. A5 was well-defined and bright white throughout, growing in length from 10° to 14°. The one p. A2 had begun as a small light spot in 2021 Dec, and was still dull in JunoCam images at PJ39 & PJ40, but was a distinct white oblong from 2022 April (PJ41) to August. But it was only dull white again in Sep. & Oct., and disappeared in Nov.

There were FFRs just p. the three isolated AWOs (A1, A7 & A8), and small ones trapped between A2-A3-A4, as marked on the JUPOS chart. All lasted throughout the apparition. except for the FFR just p. A1, which ceased to be visibly active in Oct. in ground-based images, though a remnant was visible in Junocam maps.

A tiny AWO existed p. A8 from June to Sep., wandering to and fro on the S edge of the FFR there. The Sep.29 map shows it in contact with both the FFR and A8, and it may have then merged with A8.

Dark features were as follows (see JUPOS chart in Fig.12).

There were plenty of well-defined slow tracks, for small dark spots influenced by the ‘retrograding jet’ of the S2 domain (as in the S1 domain) [although in S2 there is only a velocity minimum, not a jet with positive DL2]. These occurred in the sectors f. A1 and f. A8, from June to the end of Oct., with some residual activity f. A8 thereafter. They may have consisted of dark material emanating from the FFRs p. each of these AWOs, as in the ‘Sf. tail’ of a turbulent STB segment. Their average speed was DL2 = -15.3 (±3.4; N=8) (range -10.5 to -20.8).

F. A8 there was a long, very dark ‘SSTZB’ from May to July, which may have been a ‘Sf. tail’ of the FFR p. A8. In July it broke up into the slow-moving dark spots mentioned above, and also a spot we call ds1, which had an interesting history.

ds1 was a small, very dark brown, cyclonic spot with typical SSTC drift (DL2 = -27.6 --> -30.8 --> -26.1). JUPOS analysis shows that its latitude ranged from 38.2 to 38.5°S in accordance with the cyclonic gradient. (see Figures 13 & 14). It first developed in early July as it was about to pass oval BA (Fig.14A). At the end of Oct. it collided and probably merged with a very small cyclonic white oval f. it (Fig.14B, & Report no.5). Then it was fading in Dec., and during Jan. it dwindled to become a small, light brown spot with a white collar (see Report no.5, Fig.4, where it is indicated by a pink arrowhead, just south of STB WS6). By late Jan. it was a dull white cyclonic oval (Fig.14C), as also shown in the PJ49 map (March 1). So this was a typical example of a dark spot fading through reddish to white.

A second very dark brown spot was Nf. A7 in June-Sep. (well viewed by JunoCam at PJ44). It was red-brown at the end of Sep.(Figure 2), fading in early Oct., and then lost into the adjacent FFR p. A8.

S3 jet

This jet was quite active. It carried six small round white spots in June-July, with mean DL2 = -95.6 (±3.7; N=6) (range -89 to -98) at 43.9 (±0.2)°S, i.e. on the anticyclonic side (see ZDP in Figure 16). And from June to Jan. it carried numerous small dark spots, which were tracked in a single 70°-long longitude band that moved with the SSTC. This band was f. SS-AWO-A8, as far as the FFR p. A1, a sector in which the SSTZ was unusually clear and white, apart from the small slow-moving spots described above. So these S3 jet spots, possibly emanating from the FFR p. A1, were more visible here than they would have been elsewhere. They had mean DL2 = -97.8 (±6.5; N=15) (range -85 to -104) at 42.9 (±0.1)°S, i.e. on the cyclonic side. There were a few short-lived dark spots with similar drifts in other sectors.

S3 domain

Although this domain used to show little detail in amateur images, modern images allow us to track plenty of features and confirm that it has the classical organisation as outlined in the Introduction. In 2022/23 it did show a visible belt and zone (S3TB, S3TZ) in the canonical latitudes.

The cyclonic belt latitudes contain many FFRs, which can be resolved in the very best amateur images, notably the map from Oct.1-6 by Damian Peach (Figure 2). Their full extent is only revealed by JunoCam maps (Figure 3), which show that their boundaries often change greatly between perijoves. Where the same ones can be recognised, as between PJ43-PJ44-PJ45, they show only small movements p. or f. in L3; i.e., DL3 ~ 0 (DL2 ~ -8). This is consistent with the zonal slow current (S3TC), whose mean speed is DL2 = -8.3 (1900-1979) or -9.9 (2002-2012) [ref.1].

The JUPOS chart for the S3 domain (Figure 15) appears similar to that for 2021/22. It shows little sign of the S3TC, evidently because dark belt segments were almost absent. There was only one well-defined, very dark brown streak, prograding with mean DL2 = -27 (Aug-Oct.), and a shorter one which decelerated from ~-27 to -12 (Sep-Nov.), both rather northerly at 46°S. Other, short-lived and less distinct dark streaks (shaded on the JUPOS chart) were apparently darkened FFRs, at 46-47°S, and they had drift rates ranging from -2 to -17, with average -10, close to the mean for the S3TC.

The most numerous tracks on the chart are for small dark retrograding spots at 48-50°S, all around the circumference. The most distinct ones had mean DL2 = +12.3 (±2.3; N=13), but the full JUPOS analysis (Figure 16) reveals a continuous range of speeds from DL2 = +42 to -15, closely fitting to the Cassini ZWP. We have often suspected that these small dark spots are generated from the FFRs in this domain, although in 2022/23 both spots and FFRs were too widely distributed to infer any association.

There were two AWOs, both bright white: AWO-1, which is large and long-lived; and AWO-2, which was smaller. As in most high-latitude domains, these AWOs show a range of drift rates from the ZSC up to much faster speeds when at higher latitudes, sometimes with rapid transitions between them. S3-AWO-1 in 2022/23 had drifts alternating between fast (DL2 = -38 to -51) and slow (DL2 = -4 to 0), with latitudes varying from 51.0°S to 49.5°S accordingly. AWO-2 showed similar alternation, between DL2 = -53 and +4.

S4 jet: measurement of a large-scale wave-train

For the first time, we recorded a dark spot moving close to the full speed of the S4 jet. It was tracked with DL2 = -118 deg/30d, from June 28 to July 11, at 51.6°S (±0.4°; n=7). It can be seen on the PJ43 map in Figure 17.

This jet has not previously displayed distinct prograding spots, but it always marks a sharp boundary at 52-53°S between the visibly light S3TZ and the dark S4 domain and polar regions. Occasionally there are large-scale visible waves on this boundary. In 2022 we were able to establish the phase and group speeds of this wave-train from JUPOS measurements, and found that it represented a disturbance moving with almost the full speed of the jet. Maps in Figures 17 & 18 show it well. These features were all measured and analysed by G.A. within the JUPOS database.

The waves were measured as dark bulges and bright bays in the visible boundary at 52-53°S, plotted in Figure 19. The mean wavelength was 14° (±1.5°). The phase velocity was DL2 = -27 (±4) deg/30d (u_3 = 5.8 (±1.2) m/s). The group velocity was DL2 ≈ -96 deg/30d.

The JunoCam maps in Figure 17, especially at PJ45 (Sep.29), showed that most of the bulges enclosed a cyclonic structure in the S4 domain, whether turbulent (FFR) or dark (barge). These were probably moving with the same speed as the waves, according to our measurements on similar features (see next section).

Discussion:

These features are likely to be Rossby waves on the S4 jet, as has been argued for similar wave-trains on the S6 jet and in the NEB [see **Appendix**]. The situation appears similar to the wavy S6 jet and adjacent FFRs in the southernmost belt [ref.6]. There, however, the waves and the FFRs appear to have different speeds (u_3 ~ 0 to +10 m/s for the waves, − 3 to − 6 m/s for the FFRs; thus DL2 ~ -8 to -58 deg/30d for the waves, ~+14 to +22 for the FFRs). As FFRs in the southernmost belt often appear to be spilling turbulent material into the S6 jet [ref.6], it is possible that such faster-moving surges from the FFRs may move at the same speed as the waves.

These wave-trains have only occasionally been carefully observed before [see **Appendix**]: in images from Voyager 1 and by Cassini (in the UV, with different appearance, but with wavelength and phase velocity very similar to ours in 2022), and by amateur imaging in 2009 (not yet analysed) and 2016 (ref. our final report). Our results for 2016 were almost identical to this year's. The excellent agreement shows that this year's results are representative of this phenomenon.

The group velocity of ~-96 deg/30d indicates that these waves are transiently excited by a disturbance that moves with almost the peak speed of the S4 jet. (The peak speed of the S4 jet is DL2 = -129 to -157 deg/30d, from different spacecraft [ref.1].) However, the JunoCam maps do not show any obvious sign of this disturbance, so the origin of the waves remains unknown.

S4 domain

The S4 domain was similar to the S3 domain in 2022/23, and to both domains in 2021/22; the conclusions are largely the same, except for a difference in the ZDP profiles. Figure 16 shows the ZDP for both the S3 and S4 domains.

In the northern half of the domain, at ~55°S, the JunoCam maps show many FFRs but they are mostly quite small, and cannot be confidently traced from one perijove to the next. At any one time there were also several well-defined dark brown streaks or 'barges' in about the same latitude, representing quiescent phases of similar cyclonic circulations. These were tracked in amateur images by JUPOS [dark blue points or bars in Fig.20 (JUPOS chart); black squares in Fig.16 (JUPOS ZDP)]. They had a variety of drifts, sometimes paralleling an adjacent small AWO or S4-LRS-1, but not clustering into any distinct ZSC. Most of them were strongly prograding (DL2 ranging from -10 to -34). In 2021 the JunoCam maps suggested drifts of DL2 ~ -15 to -16 for S4 FFRs (unpublished results), so there is at least some suggestion that these small FFRs are prograding, unlike in other high-latitude belts (N4, N5, & northernmost and southernmost) where the FFRs are retrograding.

As in S3, the most numerous tracks were for small dark spots retrograding in the middle of the domain (south of the FFRs), at -56.7 to -58.5°S, with mean DL2 = +9.8 (±3.5; N=20). Some of these were gradually migrating southward within this band where the ZDP is flat.

There were two major AWOs, both thoroughly tracked: the reddish LRS-1 which we have tracked for decades, and the smaller, bright white AWO-2 which is more recent (Figure 20). *S4-LRS-1* varied in speed between DL2 = +5 and -42, following a ZDP parallel to the Cassini ZWP but slightly further south (as did smaller AWOs). JunoCam maps show that when it was moving rapidly (May 23, Aug.17, Nov.6) it was more elongated; when it was moving slowly (Sep.29, Jan.22) it was more circular and at lower latitude; on July 5 it was intermediate. Curiously, the similarly variable track of S3-AWO-1 paralleled that of S4-LRS-1 for long intervals, especially closely when both were slow-moving throughout Sep.(with a dark S4 barge poised between them; Figure 18) and during most of Jan. This is not the first time that we have noticed such parallelism between S3 and S4 ovals.

S4-AWO-2 varied similarly in speed, between DL2 = -2 (May-Sep.) and ~-30 (in Nov.). JUPOS charts and JunoCam maps since 2016 show that there is usually such an AWO in addition to LRS-1, but it is not permanent. A similar bright AWO almost certainly merged with LRS-1 during solar conjunction in 2018/19, then there was no similarly large AWO until the end of 2019, according to JunoCam maps. The present AWO-2 only became prominent around 2021 August, and JunoCam maps suggest that it became larger between PJ38 (2021 Oct.16) and PJ39 (2021 Nov.29) by merging with a much smaller AWO. It was then clearly tracked in JunoCam maps through solar conjunction into 2022.

Several smaller white spots can also be followed on the JUPOS chart (Fig.20) identified as tiny AWOs in the JunoCam maps. Two were first identified adjacent to each other on June 20, and then diverged in different latitudes; but they could have existed before (as suggested by JunoCam maps), but swung round each other onto new courses on June 20 (see PJ45 map in Figure 17), in accordance with the ZWP. One prograded with DL2 ~ -29 at 60°S (with fluctuations), and probably merged with AWO-2 on Sep.18-21 (last seen alongside AWO-2 on Sep.16 & 18: A. Cidadao). The other retrograded with DL2 = +10 at 58°S until late August, then oscillated, until it probably merged with AWO-1 between Dec.9-15 (last seen nearby on Dec.9: T. Olivetti).

Appendix: Waves on the S4 jet

The previous records of the waves at 52-53°S, on the S4 jet, are as follows:

Sanchez-Lavega et al.(1998) [GRL 25, 4043], in Voyager 1 UV images (1979). (They said these were "barely visible".)
Li et al.(2006) [Icarus 185, 416], in Cassini UV images (2000). (These were in the mid-UV filter, UV1, and they appeared as diffuse bright/dark patches, not undulations; the IR-continuum filter (CB3) did not show them.)
Rogers et al.(2014) [ref.1] summarised the two wave-trains of undulations that were observed in 2009, "modestly prograding".
Rogers & Adamoli (2016) [ref.7] measured these waves in our final report for 2015/16. The phenomenon was identical to what we report in 2022. Since then, we have not described them until the present report.

Their parameters were as follows:

1979 (UV): Wavelength = 15.5 (±1) deg;
Phase vel. DL2 = -23 (±7) deg/30d, u3 = 4.5 (±2) m/s.
2000 (UV): Wavelength = 19 (±1) deg;
Phase vel. DL2 = -25 deg/30d, u3 = 4.2 m/s.
2009: Phase vel. "modestly prograding" but not measured (yet).
2016: Wavelength = 15 deg;
Phase vel. DL2 = -27 (±7) deg/30d;
Group vel. DL2 ≈ -112 (±12) or ~-94 deg/30d.
2022: Wavelength = 14 (±1.5) deg;
Phase vel. DL2 = -27 (±4) deg/30d, u3 = 5.8 (±1.2) m/s;
Group vel. DL2 ≈ -96 deg/30d.

The peak speed of the S4 jet is DL2 = -129 to -157 deg/30d, from different spacecraft [ref. 1].

References

1. Rogers J, Adamoli G, Hahn G, Jacquesson M, Vedovato M, & Mettig H-J (2014). 'Jupiter's southern high-latitude domains: long-lived features and dynamics, 2001-2012.' http://www.britastro.org/jupiter/sstemp2014.htm

2. Rogers J (2013), 'Reference list of Jupiter's Jets' https://britastro.org/jupiter/reference/jup_jets/ref_jets.htm

3. Porco, C. et al. (2003), 'Cassini imaging of Jupiter's atmosphere, satellites and rings.' Science 299, 1541-1547.

4. Foster C, Rogers JH, Mizumoto S, Casely A, & Vedovato M (2020), 'Jupiter in 2019, Report no.10: The Great Red Spot in 2019 and its interaction with retrograding vortices as monitored by the amateur planetary imaging community.' (Part I) **https://britastro.org/node/22552**

5. Sánchez-Lavega A et 21 al.(2021), JGR-Planets (2021) vol.126 (no.4), e2020JE006686. 'Jupiter's Great Red Spot: strong interactions with incoming anticyclones in 2019' http://dx.doi.org/10.1029/2020JE006686

6. Rogers JH et al.(2021/22), 'Flow patterns of Jupiter's south polar region.' Icarus 372, paper 114742. https://doi.org/10.1016/j.icarus.2021.114742

7. Rogers J & Adamoli G (2016) 'Jupiter in 2015/16: Final report.' https://www.britastro.org/node/8263

Figures

Figure 1. Standard names and latitudes of the domains, jets, belts & zones, referred to the zonal wind profile from Cassini (ZWP: ref.3) and a map from 2022 Aug.20.

Figure 2. Maps of the southern hemisphere from amateur images, 2022 May to 2023 Jan., produced with the JUPOS software by Rob Bullen unless otherwise stated; mostly taken from our previously posted reports. Features are labelled on some maps.

Figure 3. Maps of the southern hemisphere S of the GRS from JunoCam images, from PJ41 (2022 April 9) to PJ49 (2023 March 1), copied from our previously posted reports.

Figure 4. JUPOS chart for the SEBn jet. Grey arrows mark the putative S. Equatorial Disturbance (SED). On all JUPOS charts, black = dark spots, green = bright spots, unless otherwise stated.

Figure 5. Maps of the SEBn (in System 1). Green arrows mark the putative SED.

Figure 6. Chart of spots in the GRS region, by Shinji Mizumoto (ALPO-Japan), including spots on the SEBs and STBn jets, and the Hook f. the GRS.

Figure 7. JUPOS chart of the STropZ.

Figure 8. Charts of the drift (A) and length (B) of the GRS, by Shinji Mizumoto (ALPO-Japan). Chart (A) is plotted in a frame moving with DL2 = +1.7 deg/30d. It includes the Hook f. the GRS, and the rift or 'chimney' in the Red Spot Hollow due N of the GRS, which continues to appear and move in synchrony with the 90-day oscillation of the GRS.

Figure 9. Maps of the GRS region, by Kuniaki Horikawa (ALPO-Japan), in 2022 August & thereafter, showing the Hook & Collar, and other phenomena. *South is up.*
(A) A red flaking event. A retrograding SEBs ring enters the RSH on July 31; the flake appears at the f. end on Aug.3-6, then travels round to appear at the p. end on Aug.8-11. Also note tha jagged waves prograding on the STropB p. the GRS. (This is an expanded version of Fig.13 in our Report no.3.)
(B) Over the same period, a prograding STBn jet spot (cyan arrowhead) approaches the Hook and recirculates to retrograde on the SEBs.
(C) A STBn jet spot slightly further south does not recirculate but proceed straight into the Collar.
(D) Changing aspects of the Hook from Sep. to Nov.

Figure 10. JUPOS chart of the STBn jet, overlaid with the STropZ chart (Fig.7).

Figure 11. (A) JUPOS chart of the S. Temperate domain. (B) JUPOS chart of oval BA, in a system moving with -17.3 deg/30d relative to L2.

Figure 12. JUPOS chart of the S2 (S.S. Temperate) domain.

Figure 13. JunoCam maps of the S2 domain (from Fig.3), realigned by DL3 = -19 deg/30d (DL2 = -27 deg/30d) to approximately match the SSTC.

Figure 14. Images showing SSTB spot ds1 (pink arrowhead) & other features. (A) Origin of ds1 in early July, while starting to pass oval BA. (B) ds1 merges with a cyclonic white oval in Oct/Nov., but remains a dark brown spot, which becomes methane-dark.
(C) ds1 has transformed into a cyclonic white oval in 2023 Jan. (and STB WS6 has merged into STB segment G).

Figure 15. JUPOS chart of the S3 domain.

Figure 16. ZDP covering the S3 jet and the S3 and S4 domains, from JUPOS data. Also included are averages for the waves on the S4 jet.

Figure 17. Excerpts from JunoCam maps (from Fig.3) showing the waves on the S4 jet and (inset at top left) the small dark spot on the S4 jet, which were tracked with JUPOS data.

Figure 18. Ground-based maps of the S2 to S4 domains, showing the wave-train on the S4 jet (indicated by the red line).

Figure 19. JUPOS chart for waves on the S4 jet.

Figure 20. JUPOS chart of the S4 domain. Some positions from JunoCam maps have been added to facilitate identification across solar conjunction.
