Jupiter in 2021/22, Report no.8: GRS and SEB

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The maps and charts used as the major basis for this report, by Shinji Mizumoto, are on the ALPO-Japan web site [http://alpo-j.sakura.ne.jp/Latest/Jupiter.htm].

Introduction & Summary

The South Equatorial Belt (SEB) in 2021 was essentially the same as in the previous two years, viz:
--the northern SEB largely quiet and pale, with only a narrow SEB(N);
--a somewhat disturbed SEB(C) component p. the Great Red Spot (GRS);
--a substantial dark SEB(S), with many rings (vortices) retrograding on the SEBs jet;
--persistent but limited convective and turbulent activity just f. the GRS, in which there were usually one or two bright (and sometimes methane-bright) plumes.
Given the static status of the SEB, this report will focus on the GRS.

The GRS has attracted attention in the last few years with its unexpected evolution. Its long-term shrinkage is now well known, but is intermittent, and the last sustained reduction in length occurred in 2012-13. For the next 6 years, the GRS (i.e. the visibly reddish oval) had a mean length of about 14.0° longitude. But in 2019, it was notably disrupted by frequent incoming SEBs rings, which stripped reddish 'flakes' off the periphery of the GRS, and the GRS shrank to an exceptionally small length of ~12.3° in 2019 May-June [refs. 1 & 2] At that time there was also a prominent dark grey-brown 'hook' feature around its f. end, from which dark material flowed around its S edge into a S. Tropical Band (STropB). However, during a lull in the influx of SEBs rings, the GRS recovered in length. Nevertheless, from 2020 March-June it resumed its shrinkage, even though the flaking events at that time were neither frequent nor conspicuous. In 2021 it again had a length of only 12.3°, which was sustained throughout the apparition (Figure 1).

By now it is apparent that the remarkable changes in 2019, and the further changes in 2021, result from three concurrent processes which are not necessarily connected:
i) Short term: Impacts of incoming SEBs rings, which sometimes strip reddish flakes from the GRS. Many SEBs rings were arriving in 2021, but we report that their effects on the GRS were mostly rather minor, as in 2020, with only a few examples of flakes.
ii) Medium term: The Hook and STropB. These occur together, at irregular intervals, on average once per 2 years or so, and last for some months [JHR, unpublished survey]. Dark material from the Hook appears to flow around the S rim of the GRS and into the STropB. In 2021, a substantial Hook with STropB was present from Feb. to July.
iii) Long term: Shrinkage of the GRS, which has been ongoing for at least a century. In 2021 it again has the smallest size ever recorded, with a mean length of 12.3° (Figure 1).

GRS appearance and drift rate

The periphery of the GRS was very disturbed in 2021, as we describe in detail below, but it must be acknowledged that hi-res imaging was needed to detect most of these phenomena.

At moderate resolution, observers saw only an unusually small GRS, surrounded by a dark Hook and STropB for the first half of the year, and with less contrast than in some years. Whereas in the last few years the GRS was particularly dark and red, in 2021 observers noticed that it was only moderately dark and reddish (a rather dull orange). The Red Spot Hollow (RSH), which is sometimes bright white, was very dull, largely filled with greyish-brown shading, at least until August when it began to clear. For a general overview of the GRS and its environs during 2021, please see the set of maps published in our 2021 Report no.5 [ref.3 – Fig.1].

The drift rate throughout 2021 was a consistent average DL2 = +1.35 deg/30d; DL3 = +9.35 (±0.06) deg/30d. The 90-day oscillation continued like clockwork (Figure 2).

The GRS had unexpectedly accelerated relative to the mean speed in 2020, DL2 = +2.3 (±0.06) deg/30d (i.e. the DL2 was less positive, averaged over the 90-day cycles). We suspected that this could be due to the Hook and associated disturbance around the GRS, which resembled the situation in 2018 when the GRS accelerated for several months due to the South Tropical Disturbance (STropD) passing it. But this time there was no organised STropD, and after the Hook dissipated in late July, the GRS did not change its mean speed.

The long-term shrinking trend has generally been accompanied by slower drift rate and increasingly dark red colour, as has been evident historically [ref.4] and especially since 2013. So it is surprising that in 2021, despite the very small size, the drift rate has accelerated and the colour has slightly faded. (Slow drift rate and dark red colour are also typical features of the GRS during SEB fading episodes [refs.4 & 5], but the SEB was not fully faded during these years and has not undergone a Revival.) So far, this reversal of the usual correlations is unexplained, and we wait to see if it will be maintained.

The 'GRS Bay Rift' or 'Chimney': This is the bright rift in the dark northern edge of the Red Spot Hollow (RSH). This feature is intermittently present, and several years ago K. Horikawa showed that it is coupled to the 90-day oscillation: it appears ("opens") during the phase when DL2 is relatively more positive (longitude increasing), and closes after the peak of the cycle [ref.6]. (It also appears, brightly, during fades of the SEB – ref.5.) In recent years, Mizumoto & Horikawa (ALPO-Japan) have monitored the appearance of the rift regularly, and confirmed this phase relationship. Moreover, the longitude of the rift varies in a very regular way during the cycle: it appears near the middle of the RSH, drifts p. until it is alongside the p. end of the GRS, then back again (Figure 2A). As the figure shows, this behaviour has been very regular during 2020 and 2021.

The Hook and S. Tropical Band

Quoting from our report on JunoCam at PJ32: "PJ32 was on 2021 Feb.21, just 3 weeks after solar conjunction.... A notable change since 2020 is the appearance of a new dark belt in the STropZ, i.e. a S. Tropical Band (STropB). The map (Figure*) shows that it extends from the GRS, which has a massive dark grey collar around its S side, emerging in turn from a dark 'hook' on the f. side. The appearance is thus typical of the emergence of a STropB from the GRS, and similar to 2019 May, when the GRS was being disrupted by incoming vortices from the SEBs jet. Shinji Mizumoto and Andy Casely have worked out that the present hook and STropB could have been induced around 2021 Jan.25 (during solar conjunction), by a large SEBs vortex that had been seen approaching in late 2020." *(reproduced here as Figure 3).

Figure 4 shows a pair of maps from early and late in the apparition. We can see that the SEB does not change significantly, but in the S. Tropical Zone, the STropB was present only in the early map, whereas an extensive outbreak of STBn jet spots is occurring in the later map. One feature of the April map is a prominent 'sawtooth' pattern on the STropB S edge p. the GRS, shown further in Figure 5. There was a similar wave-like appearance in 2019 after some major flaking events [ref.1]. At that early stage of the 2021 apparition there was insufficient data to determine their origin; but a flake emerging p. the GRS in 2021 May did generate a similar appearance [see below & Fig.9].

The Hook remained strong from 2021 March until late May, then it became more tenuous, but it persisted up to mid-July. Then it disappeared quite rapidly, probably because it was disrupted by the passage of a pair of SEBs rings through the RSH. The STropB was also strong by 2021 March, and remained so until the Hook disappeared in July. Then its f. end rapidly separated from the GRS and prograded in the southern STropZ. Full details are given in the section below ('The GRS periphery in late July & early August').

Mizumoto pointed out that the Hook resembled a S. Tropical Disturbance (STropD) when it is passing the GRS, as was observed in 2018; and indeed, two STBn jet spots recirculated from the STBn (prograding) to SEBs (retrograding) along the f. side of the Hook, in early May and early July, as with a STropD. Full analysis of these events is in **Appendix 1**. Moreover, when the Hook dissipated and the STropB detached from the GRS (no doubt indicating the cutoff of the flow of dark material from the SEBs f. the GRS), currents in the STropZ p. the GRS may have been briefly altered: a large SEBs ring, retrograding towards the GRS, suddenly drifted S and decelerated, temporarily [see section below & **Appendix 1**]. This too suggested a STropD circulation possibly re-forming p. the GRS, but this did not proceed. So the Hook was not actually a STropD, as it it did not exist before or after its presence at the f. side of the GRS, and its disappearance had no effect on the drift rate of the GRS.

Interaction with incoming SEBs rings

Figure 6 is a chart giving a comprehensive view of the spots that were impinging on the GRS from the SEBs and STBn jets, and emerging around it during the apparition. The number of retrograding SEBs rings was very high in 2021: the chart shows 28 rings arrived at the GRS from April 1 to Oct.31, a rate of 4.0 per month. This is double the rate that we recorded during well-observed months in 2019 (2.0 per month), and even more than during the Voyager 1 flyby in 1979 (2.6 per month: ref.7).

Almost all of them entered the RSH without hesitation (the main exception being in late July; see section below). They are always distorted and usually unrecognisable as they are stretched within the RSH, but some were probably tracked through to the f. end, and a few apparently re-emerged onto the SEBs to retrograde further f. the GRS: probably on April 18, Aug.8, Oct.22, according to Figure 6. (See below for the Aug.8 example.)

Two typical flakes in April caught the attention of observers, esp. Niall MacNeill and Clyde Foster. There was a reddish flake at the f. end of the GRS on April 18 (Figure 7), although it was not distinct in a methane image on April 19. Another SEBs ring, that entered the RSH on April 26, generated a reddish, methane-bright flake on April 30 (Figures 8 & 9). This also came round the S edge of the GRS to re-emerge at the p. end on May 6; this became a large

dark grey-brown spot prograding on the S edge of the STropB on May 7-22, but it was not methane-bright.

Another example of arrival of a SEBs ring, in early July without triggering a flake is in Figure 10.

A major transition occurred in late July, possibly triggered by the entry of a pair of SEBs rings into the RSH on July 15 & 18. Around July 18-20, while they induced a new brown streak at the f. end of the GRS, the Hook there was gradually breaking up, and the STropB detached from the p. end of the GRS (July 23 onwards). **See the following section** (inc. Figures 11 & 12) **and Appendix 1** for details of these events and others in late July-early August.

In July-August, an animation of maps (<Anim-j21GRSanimL2n> in **Appendix 1**) shows large grey-brown blobs wobbling at the p. and f. ends of the GRS as disturbance circulates around it; but no methane-bright flakes are recorded in this period. The dusky features around the GRS diminished in scale from August onwards as the RSH became clearer.

The only other reddish, methane-bright flake that we have noticed was in October, following the arrival of a pair of SEBs rings on Oct.17-18 (Figure 13). A small flake was visible on Oct.22-24, though not thereafter (Figure 14). (The large, very dark brown streak from the f. end of the GRS to the SEBs had developed earlier, from some other process, and did not persist long.)

Why were there not more flakes? Possibly the large numbers of SEBs rings entering have produced a steady state so that they no longer cause large-scale disruption to the GRS, while the grey-brown halo around it is the detritus of many such interactions, as we first noticed in late 2019. And/or, possibly the reduced size of the GRS means that it is no longer so susceptible to interactions with the incoming rings.

STBn jet spots: A few dark spots in the STBn jet had passed the GRS in Aug. & Sep. [ref.3]. (A dark spot that appeared in the STropZ immediately p. the GRS in late August was a STBn jet spot that had just squeezed round the S side of the GRS. likewise, one that appeared on Oct.28 and persisted into Nov.) Then in Oct., numerous STBn jet spots started streaming past the GRS, coming from the active region in the STB that we call DS7 or Clyde's Spot or, as it grows in the future, STB segment G (Figures 13&14 & ref.3). The STBn jet spots move north by ~2° latitude when they emerge p. the GRS (Figures 13&14). DS7 itself passed the GRS in Dec. These spots did not appear to affect the GRS.

The GRS periphery in late July & early August

A series of changes happened around the GRS from mid-July to mid-August, involving the disappearance of the Hook and detachment of the STropB. They are shown in detail in Figures 11 & 12. Remarkably, these changes also included STB white spot 8 [yellow triangle] erupting with a convective outbreak on Aug.7) [red triangle], immediately to the south – but there was no visible connection with the features moving around the GRS. See Report no.5 [Figs.11&12 in ref.3] for v-hi-res images of the whole region at this time.

In Figure 11, we note:
--Two SEBs rings [red arrowheads] enter the RSH on July 15 & 18; they are not traced coherently beyond the northernmost point, but could be responsible for the events over the next two weeks:
--A dark grey-brown streak bridging the f. end of the GRS to the SEBs develops from July 20 onwards, and elongates, turning more brown, with two leading (f.) ends retrograding in succession [orange arrows].
--Meanwhile, around July 18-20, the Hook is gradually breaking up (disrupted by the same events?) and the STropB detaches from the p. end of the GRS (July 23 onwards) [thin yellow arrow].
--This may have disturbed the currents just p. the GRS, as the next SEBs ring to approach the GRS suddenly decelerates and moves S on July 26 [black arrow]. It thus pauses in the STropZ, but then proceeds as described below.
--Meanwhile, a dark spot progrades along the STBn jet and GRS S. edge [orange triangle]. It does not recirculate across the STropZ, as two did when the Hook was present.
--STB spot 8 is a small white spot just S of the GRS.
--Brilliant white spots are erupting in the turbulent SEB just f. the GRS.

In Figure 12, we note:
--The ring that had paused in the STropZ interacted with the next SEBs ring that came behind it, which entered the RSH without deceleration on Aug.4, and the first ring then also entered the RSH on the next day [black & dark red arrowheads]. (See Mizumoto's report in **Appendix 1** for full details.)
--This pair of rings may have re-emerged as small dark spots on the SEBs f. the GRS; they then retrograded more slowly before disappearing, while a minor spot may have continued fully retrograding for a while. However, it is not possible to be certain that these were the original vortices; they could be new, transient spots produced where the divergent junction at the GRS f. end was further destabilised by the remnants of the original SEBs vortices.
--There is another very methane-bright outbreak in the SEB f. the GRS.
--STB spot 8 erupts on Aug.7. This was fully described in our Report no.5 [ref.3], q.v. for v-hi-res images of the whole region at this time, esp.:

Animation-1, covering 100 minutes on Aug.7, which shows the rotation of the GRS;
Fig.11: Hi-res images of the GRS, Aug.5-10, showing the pair of SEBs-derived spots in the RSH (& methane images showing 2 methane-bright spots in the SEB f. the GRS, Aug.4-7).
Fig.12: GRS & Spot 8, Aug.19-31. (There are many image pairs in 2021, including on these dates, from which the internal rotation of the GRS could be measured.)

References

1. C. Foster, J.H. Rogers, S. Mizumoto, A. Casely, M. Vedovato (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

2. A. Sánchez-Lavega et al. JGR-Planets (in press, 2021 Feb.) 'Jupiter's Great Red Spot: strong interactions with incoming anticyclones in 2019.' http://dx.doi.org/10.1029/2020JE006686 [This paper includes input from the amateur and JunoCam teams.]

3. J. Rogers (2021). 'Jupiter in 2021, Report no.5: The South Temperate Domain in 2021.' https://britastro.org/node/26450

4. Rogers JH, *The Giant Planet Jupiter* (CUP, 1995).

5. Rogers JH (2017) 'Jupiter's South Equatorial Belt cycle in 2009-2011: I. The SEB Fade.' JBAA 127 (3), 146-158.

6. K. Horikawa (2018), 'On the Periodic Rifting in GRS Bay.'
This report was presented as a talk at a workshop in London in 2018 and can be found here:
https://leighfletcher.github.io/project/rasjuno/ [follow the link to 'Google Drive']
It is also posted on the ALPO-Japan website:
http://alpo-j.sakura.ne.jp/kk21/j210106r.htm

7. Sada P.V., Beebe R.F. & Conrath B.J., 'Comparison of the structure and dynamics of Jupiter's GRS between the Voyager 1 and 2 encounters.' Icarus 119, 311-335 (1996).

Figures:

(North is up in all figures, and drift charts are plotted accordingly with longitude increasing to the left)

Figure 1. Chart of the length of the GRS, 2019-2021.

Figure 2. Charts of the longitude of the GRS, in longitude systems chosen to display the changes in its motion. (A) From ALPO-Japan: L2 + 2.25 deg/30d. (B) From JUPOS: L2 + 1.8 deg/30d.

Figure 3. Map of the GRS region from JunoCam at PJ32. (This is part of Fig.6 from our report on the PJ32 images. JunoCam has not had a good view of the GRS since then.)

Figure 4. A pair of ground-based maps from early and late in the apparition, with features of the S. Temperate domain and STBn jet labelled.

Figure 5. Maps in 2021 April, showing a prominent but short-lived 'sawtooth' pattern on the STropB S edge p. the GRS. See Fig.9 for another example.

Figure 6. Drift chart for spots around the GRS and in the SEBs and STBn jets, throughout the 2021 apparition.

Figure 7. A reddish flake at the f. end of the GRS on April 18, which is much less evident 9 hours later. Note the anticlockwise internal rotation of the GRS. (Figure by Niall MacNeill.)

Figure 8. Excerpts from the comprehensive set of maps by Mizumoto, showing the origin and evolution of a flake from the GRS from April 27 into May. (See Fig.9 for original versions of some of these images.)
A SEBs ring entered the RSH on April 26 and generated a dark 'bridge' on April 30 which Niall MacNeill recognised as a reddish methane-bright flake (black arrowhead); it was also methane-bright on May 2 (dark red arrowhead). This feature also came round the S edge of the GRS to re-emerge at the p. end as a small reddish methane-bright flake on May 6 (C. Foster's images). This became a large dark grey-brown spot prograding on the S edge of the STropB on May 7-22, but its colour faded and it was not methane-bright. On May 6-7, it was briefly preceded by a wave-like pattern similar to Fig.5 (see Fig.9). A patch of more strongly red material remained in the 'wake' just f. the Hook – but this was already there on April 29 (Fig.9) so it was unrelated to this flake.

Figure 9. Some RGB, CH4 & UV images from April 29 into May, showing higher resolution than the maps in Fig.8.

Figure 10. Another example of arrival of a SEBs ring, in early July without triggering a flake.

Figure 11. Excerpts from maps, July 11-28, showing the entry of two SEBs rings (red arrowheads) into the RSH, breakup of the Hook, detachment of the STropB (thin yellow arrow), and abrupt halt of the next SEBs ring (black arrow). See text for more details. Continued in Fig.12.

Figure 12. The map series continued: July 29—Aug.14.

Figure 13. Set of v-hi-res RGB images in Oct., including the arrival of a pair of SEBs rings on Oct.17-18.

Figure 14. Set of RGB and CH4 images, Oct.22-28, CH4 images. A small reddish, methane-bright flake was visible on Oct.22-24, though not thereafter.

Appendix 1:

>> Mizumoto's reports on the Hook and the associated phenomena resembling a Circulating Current: j210718; j220113r; j220108r).

>> Mizumoto's *animation* of GRS region maps (July30-Aug16_slow): includes the SEBs spots moving thru the RSH, & STB outbreak in spot 8.
>> Mizumoto's *animation* of GRS region maps (July-Dec) <j21GRSanimL2n.htm>.
