Final version, 2020 June 4. This is Part I (Sections 1 to 6.1). Part II will follow later.

The Great Red Spot in 2019 and its interaction with retrograding vortices as monitored by the amateur planetary imaging community

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Abstract

The 2019 observing apparition of Jupiter was notable for the apparent shedding of red strips from the periphery of the Great Red Spot (GRS), which would become generally known as the GRS flaking events. This report records and describes the amateur ground-based observations of these events. The intent is to provide a comprehensive record of the amateur observations covering not only the GRS flaking events, but also the associated events and features that were observed. Where relevant, images from the JunoCam instrument on the NASA Juno orbiter are included for comparison.

Early in the apparition, images both from amateurs and from JunoCam repeatedly revealed red strips described as 'blades' or 'flakes' which appeared to be drawn out from the west side of the GRS. They were bright in the methane absorption band ('methane-bright') like the GRS itself. This phenomenon had rarely been recorded before, but became frequent and increasingly prominent during 2019. The flakes appeared to be induced by rings (anticyclonic vortices) which travel along the retrograding jet on the southern edge of the South Equatorial Belt (SEBs) until they enter the Red Spot Hollow (RSH). We realised that the flakes typically appear several days after the entry of a ring into the RSH; the ring is deformed until it is no longer recognisable but we propose that, during this process, it draws red, methane-bright material out from the GRS. From 2019 April to June, some of the resulting flakes were very large, and appeared at the east as well as the west end of the GRS, apparently due to material or disturbance circulating round the periphery of the GRS.

Several other notable phenomena occurred in association with the flaking events. A large dark 'Hook' grew out of the SEBs on the west side of the GRS in March-April, resulting in easterly recirculation of dark material past the GRS and the development of a new South Tropical Band east of the GRS. The S. Tropical Band was complicated by transient wave-like patterns prograding on its south edge, and by the formation of two rings prograding along it, all of which were apparently related to the emergence of red flakes on the east side of the GRS. After the major flaking events, some later retrograding rings failed to penetrate to the west end of the GRS, one possibly because it was diverted north out of the RSH, and two because they drifted south in the S. Tropical Zone before reaching the RSH. But from 2019 September onwards, more SEBs rings entered the RSH and again induced red flakes. The GRS itself shrank considerably during the main flaking period, from 14^{o} long to 12^{o} long, but recovered later in the year.

I. Introduction

The Great Red Spot (GRS), Jupiter's best-known feature, is a large anticyclone that has existed at least since the early 19th century, and has been shrinking (with fluctuations) since the early 20th century. The shrinking trend became especially notable in 2013, since when the GRS has maintained an unprecedentedly small size and persistent red colour. In 2018-2019, a phenomenon that was seldom noticed before became frequent: the apparent shedding of red strips or flakes from the periphery of the GRS. These flakes were apparently induced by anticyclonic vortices impinging on the GRS from the retrograding jet in the same latitude.

When the SEB (South Equatorial Belt) is in its normal state (as opposed to its faded state), as it was during the Voyager and Cassini flybys, there is a 'rifted region' of large-scale convection and turbulence immediately f. (following = west of) the GRS, and there are usually dark spots including rings travelling west (retrograding) on the SEB south edge with the SEBs jet. The rings are known from spacecraft imaging to be anticyclonic vortices, which appear to be formed where turbulence from the 'rifted region' interacts with the SEBs jet, as was first shown in Voyager 1 images [refs.1-3]. Many of these rings travel along the SEBs jet until they enter the RSH (Red Spot Hollow) on its p. (preceding = east) side. Entry of these rings into the RSH appears to have been the most significant factor in the initiation of the flaking events that we report here.

In the first 3 months of 2019, relatively small reddish 'blades' or 'flakes' were observed on the west edge of the GRS, first imaged by the JunoCam camera on board the NASA Juno spacecraft during the flyby at Perijove (PJ) 17 on 2018 Dec.21, and particularly well captured at PJ18 on 2019 Feb.12 (Figure 1). As a result of these events, the GRS as well as any further SEBs rings approaching the GRS region were closely monitored by amateur observers. The flaking events became increasingly impressive in April and May.

These events generated substantial interest and excitement in both the amateur and professional planetary communities, and with opposition occurring on June 10, comprehensive and often high-quality coverage was achieved by amateur imagers, most notably those in the southern hemisphere. However, an immense effort was put in by many in the amateur community across the world to follow these events. The commitment, dedication and enthusiasm of all involved is acknowledged with appreciation. There was also significant public interest, with several articles being published highlighting the apparent 'shredding' of the GRS, some articles even suggesting its imminent demise.

During the course of the above main developments, there was substantial ongoing interaction between members of the amateur and professional planetary communities, with the resulting substantial amateur image database being complemented by work coming from the NASA Juno mission (specifically the JunoCam initiative), as well as the Hubble Space Telescope's Outer Planet Atmospheric Legacy (OPAL) imaging runs on June 26-27 (which occurred when there was a pause in the flaking activity), and observations by ground-based professional astronomers.

Much of this account has already been presented in reports posted on the BAA Jupiter Section web site (https://www.britastro.org/section_front/15), on the 'Jupiter in 2019' page (for amateur results) and the 'Results from Juno, 2019' page. Some of these are referenced herein as 'BAA Report no...' or 'Report on PJ...' respectively. A summary was presented at the EPSC congress in Geneva in 2019 Sep. [ref.4]. The objective of this report is to consolidate the efforts and present the results of the amateur planetary imaging and observing community as they covered these amazing events from around the world. The report covers the period from January to November 2019.

Section 3 gives detailed background about the state of the SEB and especially the retrograding SEBs rings in 2019, and three boxes explain other relevant structures: SEBs waves, the RSH 'chimney', and the STB Spectre.

Section 4 presents the observational results on the GRS region from amateur observers, along with maps of it from JunoCam at each Juno perijove in 2019. This is presented as a timeline, principally of the arrival of the SEBs rings and the subsequent flaking events, but also including the other related phenomena that occurred around the GRS. Section 5 describes the changes in size and appearance of the GRS during these events. Section 6 is a preliminary discussion of these phenomena.

Part II (to be posted subsequently), will include an expanded discussion with consideration of previous records of SEBs rings entering the RSH and of flakes from the GRS, which will be presented in Appendix 1. Appendix 2 will describe the 'pro-am' interactions that developed in relation to these topics, particularly involving the Juno mission.

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2. Methods

This report is based on amateur imaging, except where otherwise specified. Images were taken by numerous observers around the world, mostly with telescopes of ~20-40 cm aperture, using the webcam image stacking technique [refs.5&6], sometimes known as 'lucky imaging'. A variety of cameras and image processing techniques were employed. Most of the images used are in visible colour (RGB), but images in the methane absorption band at 889 nm were also taken and are important for analysis, as the high-altitude cloud of the GRS appears bright in this waveband.

Each imager uses their own specific techniques, mostly personal modifications of the generally accepted process. There is generally excellent agreement in planetary details recorded by different imagers. For example, the process employed by the lead author is as follows:

Telescope: 14-inch Celestron Edge HD Schmidt-Cassegrain. Camera: ZWO ASI290MM. Filter wheel: Xagyl motorised filterwheel with Baader RGB filter set (infrared cut), IR >685nm, CH4 889nm (20nm bandwidth). Capture: Multiple channel AVI's/SER's with duration of 45s, at ~100 frames per second. Alignment and stacking in Autostakkert2! Wavelet sharpening in Registax 6. Final post processing in Photoshop CC.

Planetary imagers are located around the globe, allowing a given region on Jupiter to be recorded on most rotations of the planet if observing conditions are good. Imagers are generally split into three main time frames: eastern (Australia & Far East), central (Europe & S.Africa) and western (the Americas), so some rotations are still missed. The intensive coverage was particularly well demonstrated by the GRS flaking events of 2019. With Jupiter at a southern latitude in 2019, most of the best quality coverage, although not all, was provided by imagers in Australia, the Philippines, South Africa and Brazil. A list of observers is on the BAA web site at: https://www.britastro.org/node/21420.

The amateur images are available via the databases of ALPO-Japan [http://alpo-j.sakura.ne.jp/Latest/Jupiter.htm] and PVOL2 [http://pvol2.ehu.eus/pvol2/]. The most complete view of the events around the GRS consists of a series of cylindrical maps made from the best amateur images on all well-observed rotations of the planet throughout the 2019 apparition, by co-author S. Mizumoto (ALPO-Japan), posted at: http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j19_Maps_Animation_GRS.htm. Much of the information herein is derived from those maps, and they illustrate the events that are not illustrated in this report. Higher-resolution maps were made approximately every 10 days by Marco Vedovato and Rob Bullen of the JUPOS team, and some of them are aligned in Figure 2.

We also show maps from the JunoCam imaging instrument on NASA's Juno orbiter; text concerning them is in brown type. Juno is in a highly elliptical near-polar orbit, makes a close pass (perijove: PJ) over Jupiter every 53 days, and JunoCam takes a series of images, which are processed and analysed by a 'virtual team' made up of several experienced NASA staff and several 'citizen scientists' worldwide. The images at each perijove are posted on the JunoCam web site [https://www.missionjuno.swri.edu/junocam] under 'Image Processing'. A report on each perijove is posted on the same web site under 'Think Tank', and on the BAA Jupiter Section web site [https://www.britastro.org/section_front/15] under 'Results from Juno'. The images, and hence the coverage of the GRS region, fall into two groups. During the close pass, features near Juno's sub-spacecraft track are imaged with very high quality and resolution, but only a small part of the planet is covered; this included the GRS at PJ7, PJ12, PJ18, and PJ21. Then as the spacecraft recedes beyond the south pole, the southern hemisphere is imaged over several hours, at decreasing resolution, sufficient to produce a map covering most longitudes down to the SEBs with resolution that is comparable to or better than ground-based imaging. The outbound imaging usually includes methane-band images as well.

The JunoCam maps of the GRS region in 2019 are all included below (starting with Figure 1). The JunoCam maps covering the whole SEBs/STropZ in 2019 were posted in BAA Report no.9.

Conventions and abbreviations used in this report are as follows, similar to those in routine BAA and ALPO-Japan reports. Standard BAA abbreviations are used for belts and zones and jets.
L2, longitude System II. L3, longitude System III. DL2, drift rate in L2 per 30 days (deg/month).
u_3, speed relative to L3 (in m/s). F., following (west). P., preceding (east).
Latitudes are planetographic (except for JunoCam maps). North is up in all figures.

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3. Context: Activity in the South Equatorial Belt in 2019

Because of the importance of rings on the SEBs jet in relation to the GRS phenomena, we begin by describing the state of the SEB and especially the SEBs edge during 2019. For several years previously (as we will explain in Section 6.1), there had been few rings on the SEBs, and only one typical ring on the SEBs jet was recorded in 2018. Also, after mid-August 2018 the convective region f. the GRS ('post-GRS rifted region') was almost inactive. In 2019, however, the rifted region resumed activity, and the SEBs rings became numerous and gave rise to the phenomena described in this report.

Jupiter went through solar conjunction on 2018 Nov. 26, and amateur planetary observers captured the first views of the planet from 2018 Dec.18, heralding the start of the 2019 apparition.

The 2019 apparition was notable for the strong yellowish to greyish-ochre coloration of the central and northern sections of the equatorial zone throughout the whole year. Conversely, the SEB was in an unusual state, in that the northern half of the belt was largely white, as though it was entering a SEB Fade, whereas the southern component [SEB(S)] was still dark, ranging from dark grey to very dark reddish-brown or brown in amateur images, and was perturbed by the resumed convective activity f. the GRS.

JunoCam images at PJ17 (2018 Dec.21), and the early post-conjunction amateur images in 2019 Jan., showed that the post-GRS rifted region still had one or two bright white spots, so the convective activity was continuing at a low level (Figure 1). But from 2019 Feb.9-18, bright spots proliferated there, and this enhanced activity was maintained thereafter. (Strip-maps of the SEB throughout 2019 are presented in Figure 2.) This activity spawned turbulence on the SEBs that developed into numerous dark anticyclonic vortices, which were carried westwards as rings on the jet. Until then, vortices had rarely been seen on the SEBs jet, but by early March there were several distinct ones retrograding at typical jet speed (DL2 = +116 deg/month) [BAA report no. 3]. A good view of some SEBs rings, as well as one that had recirculated into the STropZ, was obtained by Juno later in the year (Figure 3).

During March & April, it was noted that the SEB(S) had become very disturbed. F. the GRS, it was complex with a long dense chain of dark spots [BAA report no. 4]. At higher longitudes, there were many oval rings retrograding with DL2 ranging from +94 to +120 deg/month; these were typical SEBs jetstream spots. This could already be seen in the strip map of March 16-17. It appeared that the rings formed and developed their oval-like structure as they moved westward in the SEBs jet. The rings would continue to move westwards, eventually being carried into the Red Spot Hollow (RSH), resulting in the major dynamic interactions that were observed from April to June.

Figure 4 shows the tracks of these rings, and in the **Table** *[page 9]*, we number the various SEBs rings as well as link them with the various flaking events.

For the rest of the year, activity in the SEB continued similarly although with fluctuations. The convective activity (rifting) f. the GRS had almost died out in April, but it resumed with a new bright plume appearing immediately f. the GRS on April 28, and others progressively further west on April 30, May 7, 12, 18, 21 & 26, and after a brief lull, another one 21^{o} f. the f. end of the GRS on June 6 -- the maximum extent of the rifted region up to that time. (Some of these were recorded as bright in methane images, which is typical of the more energetic convective plumes in this region.) Thereafter, the residual turbulence contracted towards the RSH as usual, without frequent bright plume eruptions in June and July, although some plumes did appear within the turbulence close to the RSH. The sector for ~20^{o} f. the f. end of the GRS remained turbulent, and a new bright plume appeared 22^{o} f. the f. end of the GRS on Aug.29, and another on Sep.10. We illustrate this rifted sector in August (Fig.23, with a new white plume appearing) and in October (Fig.24). Therefore, convective activity continued in every month, albeit only in a short sector f. the GRS, and although the activity appeared modest, it apparently generated sufficient retrograding turbulence to maintain a supply of retrograding rings on the SEBs jet. The SEB(S) retained its dark brown/reddish-brown coloration to the end of the apparition.

In summary, the JUPOS chart for 2019 shows about 30 good tracks for retrograding SEBs jet spots (rings), with DL2 ranging up to +120 deg/mth. Those that approached the GRS are also shown on the chart by co-author Mizumoto (Fig. 4). Many of them decelerated as they approached the GRS, to different extents. This outbreak was still continuing in November.

On following pages:

Boxes— Other possibly relevant structures in the region

Box A. Waves on the SEBs

Apart from the rings (vortices), many sectors of SEBs in 2019 were marked by trains of waves, similar to those we reported in previous years; they are undulations in the retrograde jet, with phase speeds less than the jet speed [Ref.A1]. They were seen in many hi-res images near opposition, and in JunoCam images at PJ23 (e.g. Fig. 3). In the PJ23 images, the SEBs edge was deformed almost continuously by wave-trains with wavelengths 4.5° to 4.2° longitude (5000-5300 km). JunoCam's images are the best views of them ever obtained, and the streaks aligned with the waves support the conclusion that the jet itself is undulating.

Gianluigi Adamoli (JUPOS team) has now done an analysis of several such wave-trains that were well defined in amateur images, with wavelengths of 4.6° to 3.9° longitude, and phase speeds (DL2) ranging from +82 to +96 deg/mth [unpublished data]. These agree well with the relationship that we reported for earlier years [Ref.A1] and extend it to shorter wavelengths and faster speeds.

Independently, Marco Vedovato produced zonal wind profiles in two sectors from Hubble images taken on 2019 June 26-27, and found multiple speeds for the SEBs jet [BAA report no.9]:

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; and +86 is the speed of the SEBs wave-trains.

Ref.A1: Rogers JH, Fletcher LN, Adamoli G, Jacquesson M, Vedovato M & Orton GS (2016). 'A dispersive wave pattern on Jupiter's fastest retrograde jet at 20°S.' Icarus 277 (2016) 354–369. http://dx.doi.org/10.1016/j.icarus.2016.05.028

Box B. The RSH "Chimney" and its impact on the SEBs ring activity

[from BAA report no.6]

Sometimes the dark rim of the RSH is broken by a white 'rift' which curves NE into the northern SEB. (This rift also manifests itself during SEB Fades as an intermittent white spot [ref.B1].) At ground-based resolution it is usually difficult to determine whether spots are drawn into it from the RSH, but the Bilbao group have reported that this happened with one large oval that had entered the RSH from the STropZ [ref.B2]. An analysis of this white spot or rift N of the GRS, from ALPO-Japan records over many years, was presented by Kuniaki Horikawa at the RAS-Juno workshop in London in 2018 May [ref.B3]. He showed that it only appears at a certain phase of the 90-day oscillation, when the GRS has more positive drift, up to the time when it has maximum longitude, then the white spot/rift disappears again. Indeed, according to the charts by ALPO-Japan and JUPOS, the GRS adopted more positive drift around 2019 May 19 as expected within the 90-day oscillation, and the white spot/rift opened up on June 3. (See Fig.20.) So the events were nicely consistent with previously reported behaviour. The rift was also 'open' in late March, but did not prevent the formation of a flake then; but it is not surprising if there is a random element in the fate of these SEBs rings. Jupiter's atmosphere is always a balance between chaos and order, and apparently deterministic phenomena commonly arise from a series of random ones.

References:

B1. Rogers JH (2017) 'Jupiter's SEB cycle in 2009-2011: I. The SEB Fade.' JBAA 127 (3), 146-158.
B2. Sanchez-Lavega et al.(1998), Icarus 136, 14-26: 'Dynamics and Interaction between a Large-Scale Vortex and the Great Red Spot in Jupiter'.
B3. Horikawa K (2018), 'On the Periodic Rifting in GRS Bay':
https://www2.le.ac.uk/departments/physics/people/leighfletcher/ras-juno-europlanet-meeting-2018

Box C. The STB Spectre

The STB Spectre is a cyclonic circulation like its predecessor the STB Ghost, and their circulation has been well attested, esp. from Hubble OPAL map pairs [e.g. Refs.C1-C3], and from JunoCam at several perijoves. The wind speeds along the north and south edges are considerably stronger than the usual STBn and STBs jets in undisturbed sectors. The Spectre was passing the GRS from 2019 May to Oct. [JUPOS chart posted with our Report no.9], so we suspected that it could have enhanced the major east-end flaking events in May, but it would not have been responsible for the earlier ones. Its p. end had low contrast but could be defined in April as it approached the GRS (Figs. 11 & 12). Its p. end was not well defined observationally after 2019 April, because it was in a region very disturbed by the flaking events etc., but it looked closed in closeup PJ23 images in 2019 Nov.

References:

C1. Rogers J (2016), 'Jupiter's South Temperate domain....' https://www.britastro.org/node/7230

C2. Rogers J (2019 Feb.), 'Jupiter's South Temperate Domain, 2015-2018'. https://britastro.org/node/17283 (esp. Appendix A).

C3. P. Iñurrigarro, R. Hueso, J. Legarreta, A. Sánchez-Lavega, G. Eichstädt, J. H. Rogers, G. S. Orton, C.J. Hansen, S. Pérez-Hoyos, J. F. Rojas, & J. M. Gómez-Forrellad (online, 2019). 'Observations and numerical modelling of a convective disturbance in a large-scale cyclone in Jupiter's South Temperate Belt.' Icarus 336 (2020), paper 113475.

4. Results

4.1. Overview

Figure 4 shows the tracks of the SEBs rings, and in the **Table** *[page 9]*, we number the various SEBs rings and link them with the various flaking events.

The first image showing a flake in this series was taken by JunoCam at PJ17 on 2018 Dec.21, at the end of solar conjunction. Once the apparition was adequately under way for ground-based observers, in the first 3 months of 2019, three relatively small flakes were observed on the f. edge of the GRS; one was well captured at PJ18 (2019 Feb.12) (Figure 1). All followed soon after the entry of SEBs rings into the RSH.

Six rings were observed to arrive at the RSH in April and May, and most of these led to red flakes not only near the f. end of the GRS, but also – several days later – at the p. end of the GRS. The picture was further complicated because in early April, a prominent dark feature developed on the SEBs immediately following the GRS, possibly also induced by SEBs ring activity; it would become referred to as the 'Hook'. Dark material, sometimes mingled with red flake material, circulated from it around the south side of the GRS and emerged to form a new South Tropical Band, an irregular dark strip which continued to extend eastwards. Meanwhile, the flaking events became more impressive; the most spectacular flaking events took place from mid-May through to early June, at which time the GRS had a truly bizarre appearance.

Figure 5 shows the situation then in the context of the currents that are known to exist in and around the GRS. Figure 6 summarises the typical timescale of the flaking events, starting from the time that a retrograding SEBs ring enters the RSH.

After ring no.12 entered the RSH on June 1, it did not produce a flake, apparently because it was diverted north via a channel ('the chimney') that opened up into the SEB. After June 1, there were no more rings on the SEBs for some distance; it would be three weeks before the next one arrived. The next SEBs ring should have arrived at the edge of the RSH on or around June 23, but had dwindled to a small size so may have dissipated. The next (ring no.13) arrived on June 25. So at the time of the Hubble imaging on June 26-27, the GRS had had time to settle down after the extraordinary disturbances a month earlier, and indeed it had resumed its oval form and recovered slightly in size.

Ring no.13 produced a flake, and may have been the source of disturbance travelling around the GRS which produced further flakes at both p. and f. ends up to mid-July. But then, no further flakes occurred during the summer. Rings nos.14 and 15 recirculated south into the South Tropical Zone (STropZ) before reaching the RSH and so did not enter it. Finally, ring no.16 disappeared before reaching the RSH, and no others followed it for several weeks.

Further SEBs rings continued to be produced and were carried along the SEBs jet, and entered the RSH starting on Sep.8. Seven rings entered the RSH in Sep. and Oct., and produced flakes similar to those seen in the spring, although the spatial and temporal resolution of images was decreasing as the apparition neared its end. Activity was continuing up to late November when the apparition effectively ended.

The GRS underwent a significant reduction in apparent size during the main flaking period, from which it would recover after the activity died down later in the apparition (see Section 5). The GRS alterations were accompanied by changes within the GRS hollow itself, including apparent structural and colour variations. However, its drift rate and its 90-day oscillation were unaffected, apart from a small displacement in longitude for ~45 days in April-May.

4.2. Timeline, 2019 January to early April

As the apparition began, around the start of 2019, retrograding rings had already reappeared on the SEBs. A pair (rings nos.1 & 2) retrograded into the Red Spot Hollow on Jan.21 & 24; another (ring no.3) entered on Jan.30.

[Rings nos.1&2, flake no.1]: A reddish feature emerged from the f. end of the GRS on Jan.25 and (as of Feb.2) was still retrograding on the SEBs, and was methane-bright (Fig.7). This was later designated as our flake no.1. It was pointed out by Andy Casely who posted an animation of cylindrical maps from 3 observers on Jan.25-31 [https://photos.app.goo.gl/8qRrK7Yn65DtBvxm6]. Its origin was not entirely clear, as the reddish feature was largely superimposed on a dark brown streak, but it was thought to be a red, methane-bright cloud drawn out from the GRS. Just such a feature had been shown in the JunoCam PJ17 image on 2018 Dec.21 (Fig.1). This red streak continued to extend westward along the SEB(S), but also, in most good images (although they were only taken every two days at this early stage in the apparition), remained linked to the f. end of the GRS, at least up to Feb.12. In retrospect, this apparent linkage could have represented an additional flake (unnumbered) induced by the entry of SEBs ring no.3 on Jan.30.

[Ring no.4, flake no.2]: **Juno at PJ18 (Feb.12)** flew just 3 deg f. the f. end of the GRS, and JunoCam obtained excellent closeups (Figs. 1 & 8). Along the SEB(S) f. the GRS, there were red streaks intermingled with more typical grey-brown SEB(S) material, possibly representing remnants of the January flake(s). More obvious was a new flake (no.2) at the f. end of the GRS. (Clyde Foster said it "almost looks like the GRS is shedding repeated 'turbine blades'.")

On Feb.12, an RGB image (Fig.9) did not clearly show the flake as red but it was just resolved (bright) in P. Miles' IR and CH4 images. Observers were not able to get v-hi-res images until Feb.18-21, when a reddish streak could be seen from the GRS to the SEBs (apparently bright in CH4 on Feb.21) – possibly the same one seen at PJ18, now extended.

In the ground-based images alone, the flake was so small that one would not have noticed anything unusual. Nevertheless, it confirmed that production of these 'blades' had recently become a frequent phenomenon.

[Ring no.5, flake no.3]: Ring no.5 entered the Red Spot Hollow on March 23; a red flake (no.3) commenced around March 27. This is shown in Fig.10. Red material also emerged at the p. end of the GRS (April 1-6) (Figs.1 & 10).

Juno at PJ19 (April 6) (Fig.1) took images in RGB and CH4 which clearly showed the extent of the red, methane-bright material. The expanded material f. the GRS had become very elaborate by this time, and the methane map suggests that the material p. the GRS also derived from the same red flake, which had flowed ~270^0 around the GRS by April 6.

Table:

2019 GRS flakes and related events											by Shinji Mizumoto @ALPO-Japan
Flake No.	SEBs ring No.	SEBs ring enters RSH	Flake appears GRS N/W=f.e.	Flake appears GRS E=p.e.	Flake CH4 image	STrB streak	RSH rift 'Chimney'	RSH f.e. 'Hook'	RSH f.side SEBs flow	GRS length	Notes ( ) : estimated
0	-----	?	?	?	?	(-----)	(close)	(-----)	(flow existence	14°	Imaged at Juno PJ17 / 2018 Dec.21.
1	1,2	Jan.21,24	Jan.25	-----	bright	-----	close	-----	flow existence	14°	
2	4	Feb.8	Feb.9~12	-----	bright	-----		-----		14°	Small event. Imaged at Juno PJ18 / 2019 Feb.12.
3	5	Mar.23	Mar.27	Apr.1	bright	-----	Mar.4 open	Apr.1? appear	Apr.1? no flow	14°	SEBs ring-5 affected by RSH rift?
4	6,7	Apr.12,15	Apr.15~17	Apr.22*	bright	Apr.3 appear				reduce	Large event. *Very dark grey collar, emerging on p. side Apr.22, with red streak in it by Apr.25.
5	8	Apr.24	Apr.30	May 6	bright		Apr.24 close			reduce	Small ring, small flake, but notable flake p. GRS from May 6.
6a,b	9	May 13	May 17	May 21~23	bright					12°	Large event.
---	10	May 18	-----	-----	-----					12°	Only minor features resulted.
7a,b	11	May 22~23	May 25~26	May 30	bright					12°	Large event ; 7a connected to 6b.
8a,b,c	12	Jun.1	(Jun.8?); Jun.20~21	Jun.15~17	slightly bright		Jun.3 open			12°	SEBs ring-12 diverted up the RSH chimney? New flake appeared at p.end of GRS on Jun.15~17, & travelled round N side to appear at f. end on Jun.20~21, possibly from disturbance travelling round the GRS with P ~ 9-10 days.
9a,b	13	Jun.25	Jul.1	Jul.4	sl. bright					12°	Flake at f. end on Jul.8, and at p. end on Jul.12~14, possibly due to disturbance continuing around GRS with P ~ 9-10 days.
9c,d			Jul.8	Jul.12~14	sl. bright			Jul.5 disappear			
---	14,15 16	-----* -----**	-----	-----	-----	Jul.12	Jul.12 close	-----	flow existence	increase	*Jul.12~ Shift rings-14,15 south → STrB. White cloud approach from STB to GRS p.e.? **SEBs ring-16 disappears / Aug.18?.
---	17	Sep.8	Sep.13	Sep.18	sl. bright	-----	Sep.9 open	-----		increase	Flake : small
---	18	Sep.18	Sep.24	Sep.30?	?	-----		-----		increase	Flake : small
---	19	Sep.23	Sep.28?	-----	?	-----		-----		increase	?
---	20	Oct.1	Oct.5	Oct.11	sl. bright			-----		14°	Flake : mod.large
---	21	Oct.3	Oct.8	-----	?	-----		-----		14°	
---	22	Oct.9	Oct.12	-----	?	-----		-----		14°	
---	23	Oct.17	Oct.22*	Oct.30**	sl. bright	-----	Oct.14 close	-----		14°	*Dark spot / Oct.27 **Imaged at Juno PJ23 / 2019 Nov.3
---	24	Nov.1?	?	-----	?	-----		-----		14°	

Following this event, maps made by co-author S. Mizumoto, posted on the ALPO-Japan web pages [http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j19_Maps_Animation_GRS.htm] implied that these flakes were induced by the arrival of the retrograding rings on the SEBs jet. Mizumoto's maps included a constantly updated set centred on the GRS, with relevant features marked, including the reddish flakes that detached from the f. end of the GRS, and the retrograding rings on SEBs that arrived at its p. end. He found that each of the three successive flakes in early 2019 was formed within a few days after a retrograding ring entered the RSH. The only examples of these features from 2019 Jan. to March were those described above and listed in the **Table** (rings nos.1-5, flakes nos.1-3), so their regular relationship in time is highly significant. These three examples gave us a strong indication that the flakes were induced by the incoming SEBs rings, and subsequent events confirmed this hypothesis, although they would become more elaborate in the following months. We concluded then [BAA report no. 4] that that these vortices were disrupting the periphery of the GRS, and the red flakes lasted for more than a week, detaching from the f. end of the GRS and extending in the f. direction (westwards) within the SEB(S). Their reddish colour was often difficult to distinguish from the brown of the belt but they could be identified as methane-bright. Similar features had been seen in some previous years, but only rarely. So the appearance of several of them so soon since solar conjunction was notable.

4.3. Timeline, 2019 April to early July

[Rings nos.6&7, flake no.4:] In early April, another pair of retrograding rings was observed approaching the RSH. They entered it on April 12 & 15. Indeed they triggered the emergence of a pair of red flakes from the GRS (April 15-20) (Figs.2 & 11). However, the interaction became more complex. **A large dark hook-like structure**, which became known as the 'Hook', developed on the southern edge of the SEB immediately f. the GRS. (It was not methane-bright.) Some of the dark material in this Hook streamed around the south edge of the GRS, forming a very dark grey collar around the GRS (which then looked like a giant red eye!), and thence prograded as a **South Tropical Band (STropB)** preceding the GRS.

The Hook was a southward projection from the SEBs at the f. end of the RSH, which began to develop as a complex projection from late March into early April, and rapidly extended anticlockwise around the S side of the GRS. Although there is often a hump in this location, this one attracted particular attention as it contained internal disturbance and came to strongly resemble the S. Tropical Disturbance (STropD) a year earlier. It extended around the GRS to create a patchy STropB emerging Sp. the GRS from April 12 onwards. This was a dynamic stream with multiple concent-rations and extensions, again reminiscent of the STropD. With the flaking event no.4 in mid-April, the flake itself f. the GRS was very dark brown and only weakly methane-bright, and it may have contributed both red and dark material that circulated round the south side of the GRS to enter the STropB p. the GRS around April 22-24. Fig.12 shows the period April 24-28 in detail. Thin tendrils of light reddish, weakly methane-bright material can be seen p. the GRS, possibly a curved flake still attached to the GRS at its N end as well as a streak prograding with the dominant dark grey material of the STropB. At the same time, the red flake f. the GRS (no.4) was spreading and curling in the SEB to the west, much as in the PJ19 JunoCam map; red flake material persisted here into May (Fig.13). Thus, flake no.4 was the first of the larger events, and also produced material p. as well as f. the GRS.

[Ring no.8, flake no.5:] (Fig.13) Meanwhile, a small ring (no.8) entered on April 24 and triggered a small flake (no.5) at the f. end on April 30. At the same time, the red material from one or more flakes did persist in the SEB f. the dark collar. Red material was also discernible in a diffuse fringe tracking around the GRS S edge inside the collar from May 1-5 until it emerged as a red, methane-bright streak p. the GRS on May 6-7. Marco Vedovato's animation [http://pianeti.uai.it/images/J_Map_L2_2019_GIF.gif] suggests that this circulating red fringe and notable flake at the p. end may have been derived from the small flake no. 5 at the f. end, having circulated completely around the GRS.

[Ring no.9, flake no.6:] (Figures 14-18) On May 13, a large SEBs ring entered the RSH. As it swung round in the RSH, a flake began to separate from the GRS N edge on May 15, and on May 17 this emerged at the f. end as a large red methane-bright flake, as predicted. It became very conspicuous on May 19-20 as its f. (west) part retrograded on the SEBs away from the GRS, while its leading end remained attached to the GRS and continued to orbit around it. The leading end probably squeezed around the S edge of the GRS on May 20, and then became the large red flake that emerged from the p. end of the GRS on May 21-23 (as the previous one had done on May 6-7). The appearance on May 22 & 23 was bizarre! Also, traces of disturbance may have been circulating completely around the perimeter of the GRS, so the erosion or splitting on its N side, which observers pointed out on May 22, could have been due to one of the earlier disruptions.

Figures 14&15 show RGB images (unprojected) from May 12 to 22. Fig.14 shows representative images with an hypothesis as to how the vortex from the SEBs, or (more likely) a less organised remnant of it, drew the red material out of the GRS. Fig.15 shows the subsequent distribution of the red material. These original images have higher resolution than most posted maps. The methane images show the red flake at higher contrast though lower resolution; they are not all included here as they are fully represented in Mizumoto's maps. Fig.16 identifies all the features on May 20. Fig.17 shows the remarkable scene on May 22-23 in full multicolour image sets by several observers. The fate of the flake having emerged at the p. end on May 23 is best shown in methane maps (Fig.18): while its outer end elongated along the STropB, its inner end remained attached to the GRS and continued orbiting around it, returning to the f. end on May 26, 9 days after it first appeared there – and coincident with the next flake that was just appearing. The long-drawn-out flake no.6 thus formed a reddish, methane-bright line running through the RSH, while its p. end continued to elongate along the STropB, spanning >30^{o} longitude (Fig.18).

Co-authors Mizumoto and Vedovato both produced long animated series of maps which show these events. Their animations are at:
http://alpo-j.sakura.ne.jp/Latest/j_Cylindrical_Maps/j19_Maps_Animation_GRS.htm
http://pianeti.uai.it/index.php/Jupiter:_2019_Animated_gif

SEBs ring no.10 was a small one that entered the RSH on May 18 but only minor features were produced.

[Ring no.11, flake no.7]: On May 22-23, while flake no.5 was so impressive, ring no.11 entered the RSH (Figs.15&17), and 3 days later, another large flake (no.7) duly appeared at the f. end of the GRS (Fig.18). Over May 28-31, this could be seen propagating round the S edge of the GRS as a narrow dark red-brown streak, which emerged impressively at the p. end on May 30-31. From May 22-30, the GRS looked quite extraordinary (Fig. 18). Like the previous flake at the p. end, this one became a large red-brown, methane-bright protrusion which elongated rapidly in the STropB; it also had a series of wave-like projections on its S edge (*see Section 4.4.1 below*).

PJ20 (2019 May 29): The GRS was captured in the outbound images (Fig.19), in RGB and CH4. which showed the complexity of the red, methane-bright streaks that resulted from the last two detachments of flakes. At least one of them was wound completely round the periphery of the GRS, while fragmenting streaks from them could be seen up to 35° longitude p. the p. end of the GRS. The same appearance was shown by C. Go's images on the same date (Fig.18).

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After mid-May, the SEBs p. the GRS was much less disturbed. There was only one more retrograding ring there (about 30° p. the p. end of the GRS on May 22). On the actual SEBs edge, there was now a beautiful long train of waves (*see Box A, above*). So it appeared possible that the activity would die down for a while – as it did.

Moreover, after the end of May, things took an unexpected turn. The next ring (no.12) entered the RSH on June 1-2, but it did not induce a flake; instead, it appeared to have been at least partly diverted northwards, through the white rift in SEB(N) that appeared at the northern point of the RSH on June 3 (*see Box B, above*). Observers (putting north up) took to calling this the 'chimney', and Mizumoto's animated maps suggest that the ring was partly diverted 'up the chimney'.

However, notable phenomena continued to occur p. the GRS, as described in the next section. Briefly:

--The very dark S.Tropical Band (STropB) had emerged on the p. side of the GRS in mid-April, elongating rapidly as its p. end prograded, and was still prominent.

--On the S side of the STropB, in May & June, there were sometimes striking chains of dark spots, looking like wave-trains (Figs. 5, 18, 20). The dates when they were seen turned out to be when a red flake was appearing or had recently appeared at the p. edge of the GRS. *(See Section 4.4.1 below.)*

--The huge flakes p. the GRS from May 22-30 onwards produced persistent red methane-bright features prograding in the dark STropB, including streaks of various lengths, and at least two reddish rings that were likely to be anticyclonic vortices, which merged to produce STropB Ring no.1. *(See Section 4.4.2 below.)*

--Two more SEBs rings were approaching the GRS in July, but during July 14-17, each in turn drifted south and reversed its drift, recirculating directly to the STropB before entering the RSH. They then merged to produce the prograding STropB Ring no.2/3. *(See Section 4.4.2 below.)*

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After the last SEBs ring [no.12] had entered the RSH on June 1-2, and failed to induce a flake due to its interaction with the newly opened 'chimney', there were no more SEBs rings for three weeks. The next SEBs ring entered the RSH on June 25, and duly induced a flake at the f. end of the GRS on June 30/July 1 [Ring no.13, flake no.9].

Meanwhile, there were also several flakes that appeared at the p. or f. ends of the GRS without any incoming SEBs ring to induce them. These might have been due to disturbance that was completely circumnavigating the GRS. Thus a new flake appeared unexpectedly at the p. end of the GRS on June 15-17, and was then distinctly followed travelling round the N side, becoming a flake on the Nf. side on June 20-21 (Fig.20). Then, the flake induced at the f. end of the GRS on July 1 [flake no.9] was followed by one at the p. end on July 4-5, and at the f. end on July 8, and at the p. end again on July 12-14 – all consistent with a single distortion travelling around the GRS with a period of 9-10 days.

4.4. The S. Tropical Band and associated phenomena east of the GRS (mainly in June-July)

4.4.1. Wave-like projections on the STropB

The very dark STropB emerged on the p. side of the GRS in mid-April, elongating rapidly as its p. end prograded, and remained prominent during the major flaking events in May. On its S side, approximately in the latitude of the STBn jet, there were sometimes striking chains of dark spots or projections – looking like wave-trains – on May 5-6, May 22-23, June 3-4, and June 18-25 (Figures 5, 18, 20). On those dates, a red flake was appearing or had recently appeared at the p. edge of the GRS (see **Table**, *page 9*). So we proposed [BAA, report no.6] that the wave-trains, which extended ~12-36° in longitude p. the flake, were formed by instability on the prograding STBn jet, where the jet squeezed past the GRS and then opened out on the p. side. The constriction and instability of the jet could have been enhanced both by the flake disturbance moving around the periphery of the GRS, and by the presence of the STB Spectre alongside the GRS, which embodies a faster sector of the jet (*Box C* & Fig.5).

Gianluigi Adamoli has measured the motions of these wave-like projections on the available images in May and June, including the time periods specified above. Details will be posted elsewhere but are summarised as follows. He measured 25 tracks for individual projections, all with >5 data points. Those produced between May 1-17, including the first 'wave-train', all had rapid drifts in the STBn jet, averaging DL2 = -103 deg/mth. This is close to the global mean speed for this latitude (26.4°S) in the Cassini zonal wind profile, close to the peak of the jet. The second 'wave-train' had more diverse drifts, with the later projections generally moving slower so the series did not move coherently. From then on, all projections had the slower drift rate, averaging -79 deg/mth, although the latitude and 'wavelength' (mean spacing) were the same as before. The reason for the change in drift rate around May 20 is not obvious, but could be connected with the fact that the p. end of the STB Spectre was passing the GRS during May, thus changing the wind speed gradient alongside it.

Proj.nos.	*Dates of origin* 2019	*DL2* *(deg/30d)*	*(±SD)*	*Mean spacing* *(deg.long.)*	*Mean Lat.*
[2-6]	May 2-6	-103	3	4.8°	-26.4°
[8-12]	May 17-26	-102	16	(6.6° – irreg.)	-26.4°
[13-15]	May 30—June 8	-78	7	4.0°	-26.4°
[18-24]	June 10-22	-79.5	5.5	5.5°	-26.3°

The mean latitudes given are for the centroids of the projections; their peaks were at 26.9°S and the troughs at 25.4°S (S edge of the STropB).

4.4.2. The STropB (continued) and anticyclonic rings prograding with it

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.

As described above, 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.

In June, several disturbances just p. the GRS combined to form a persistent, prograding anticyclonic ring at ~24°S (Figures 2, 4, 20). 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 (Figure 18), from which two coherent methane-bright rings developed on the STropB north edge (Figure 20), 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 to Sep.30). (Then it accelerated again.)

During the last few days of June and the first week of July, the point where the STropB connected to the GRS moved northwards on the p. (eastern) edge of the GRS, producing a pinch point between the STropB and the SEBs off the Np. edge of the GRS. This appears to have had an influence on the flow streams in this region, and resulted in a potential recirculation loop being formed between the SEBs jet (westward) and the southerly STropZ flow (eastward) with the subsequent rings being diverted directly from the SEBs to the STropB without entering the RSH.

Thus in early July, two more SEBs rings (nos.14 & 15) were approaching the GRS, but during July 14-17, each in turn drifted south and reversed its drift, recirculating directly to the STropB before entering the RSH (Figures 4 & 21). The leading one halted in the S.Tropical Zone, 5-10^{o} p. the edge of the RSH, and reversed its drift and passed the second ring on July 14-15. On July 16-17, the second ring (no.15) also moved south instead of entering the RSH. (However, it looks as though this second, larger ring actually split on July 17, producing a minor white spot that proceeded into the RSH on July 18 and reached the northernmost point late on July 20.) Then they merged, creating this prograding Ring no.2/3 in the STropB (*see PJ21 below*). (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.) The mean drift rate of ring no.2/3 was DL2 ~ -28 deg/mth (July 21—Sep.24), oscillating, then it decelerated to ~-10 deg/mth.

These events left two dark rings at ~24°S, presumably both anticyclonic, prograding along with the STropB at ~25°S (Figures 2 & 4). As just described, no.1 was the product of flaking from the GRS into the STropB in May-June, and no.2/3 was the product of two retrograding SEBs rings that recirculated to the STropB just before reaching the GRS in July. From July onwards, 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) (e.g. Figure 3).

The dark grey-brown STropB had 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.

Meanwhile, another reddish flake (source unknown) emerged on the p. end of the GRS on July 19, detaching into the STropB on July 20 (Figure 21), although it was weak or absent in methane images. Note that these phenomena on July 20 (the day before PJ21) were comparatively small, and the GRS around this time appeared much more normal than it did 2 months earlier, with a regular oval outline, although still only 12 deg long.

PJ21 (2019 July 21): At PJ21, as predicted, Juno flew right over the GRS, just 3^{o} f. the centre. (This was Juno's second pass directly over the GRS, after PJ7.) As the view was oblique and backward-looking, the resolution was nowhere near that attained at PJ7, but the images could still be combined to make a valuable hi-res map (Figure 22). The GRS had regained its oval form, though with a ragged outline. Adjacent to it, there were just two, comparatively minor, visible remnants of the phenomena described above: a reddish flake that had emerged from the p.(east) end of the GRS on July 19-20, and a small white spot in the RSH representing a fragment of the last of the SEBs rings. The images show that the reddish flake is still attached to the GRS by a narrow reddish streak that extends all around the north half of the GRS. Two or three small 'blades' are visible at the f.(west) end of the GRS, consistent with the hypothesis that such disturbances are travelling around the periphery of the GRS, but similar small streaks can be seen in earlier HST images so they may be normal features. The images also show the last SEBs ring (no.15) just after it had recirculated south to become STropB Ring no. 2/3, p. the GRS. Along the south edge of the GRS is the STB Spectre, a much-elongated cyclonic circulation that is clearly compressed alongside the GRS.

4.5. Timeline of the flaking activity, 2019 Sep. to Dec.

[from BAA Report no.9]

Up to late July, the last flake had emerged from the p. end of the GRS on July 19 and was imaged by JunoCam two days later at PJ21 (see above). 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. (A smaller SEBs spot arrived on Aug.20 but had already almost disappeared and had no effect.) In August (Figure 23) the GRS was a symmetrical red oval, with a light brown collar around it, and it recovered somewhat in length (see below).

PJ22 (2019 Sep.12): The GRS was only partially captured at the limb as Juno passed over the SEB following it. The turbulent SEB following the GRS was well shown (Figure 25).

No further SEBs rings arrived at the RSH until early Sep. (Figure 4). Then, a series of seven 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 (see **Table**, *page 9*). 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^o in longitude from the f. end of the GRS.

Examples are in Figure R24, which shows two successive flakes at the f. end, and 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 seven 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)** (Figs.24 & 26): 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 be a recently entered SEBs ring (no.24).

JunoCam at PJ24 (2019 Dec.26): PJ24 was just one day before Jupiter passed directly behind the Sun as viewed from Earth. JunoCam images therefore provided the only view of the planet at solar conjunction. The GRS was only caught in the last, lo-res outbound images (Fig. 26). It was followed by a large red methane-bright flake; this must have been recently emitted from the GRS f. end.

5. Size and structural changes of the Great Red Spot

The GRS mean drift rate throughout 2019 was DL2 = +1.9 deg/mth, with the 90-day oscillation superimposed as usual (Fig.7). These motions were not affected by the flaking events, except that the GRS longitude was ~1 deg higher than would be expected for ~45 days in April and early May, suggesting that the GRS may have been displaced or distorted by the large flaking events then.

The GRS, as defined by the visibly red area, became considerably smaller as the major flaking events proceeded. It reached a minimum in late May-early June with a mean length of only 12.6 deg (as low as 12.0 deg in some images). K. Horikawa wrote: "As result of flaking, GRS is shrinking more and more. It's amazingly small in Chris Go's images on June 1. I got 11.3 deg. for its size. It's the minimum record of GRS in not only my measurements since 2002 but also probably its life."

Measurements of the visible GRS length were done by the JUPOS team, and by K. Horikawa and S. Mizumoto (ALPO-Japan). Plots of the GRS length in 2019 are in Fig.28, produced independently by ALPO-Japan and JUPOS recorders. It was 14 deg long in early 2019 (JUPOS: 14.1 ±0.6, Jan.30-May 18). It shrank dramatically and quite abruptly in late May, when the largest flaking events were occurring. The mean length was 12.6 ±0.5 deg in late May and in June (May 23-June 26, JUPOS), until it recovered substantially during July, and then more slowly until October, when it regained its original value of 13.9 ±0.5 deg (JUPOS, Sep.16-Oct.10).

The minimum was the smallest apparent size yet attained by the GRS. Fig.29 shows the length since 2010 or 2011 (again, plotted independently by ALPO-Japan and JUPOS recorders). This shows the much-publicised shrinkage in 2012-13, which led to a mean length of 13.6 deg in 2013-14 [refs.7&8]. After that it was fairly stable, recovering slightly to 14.2 ±0.6 deg [JUPOS] in 2018, which still held up to 2019 March. So the rapid shrinkage in 2019 May was really exceptional.

There was also a small shrinkage in the width in latitude, as plotted from JUPOS data in Fig.30. The panels on the right show the latitudes of the N and S edges, and the distance between them, in 2019. The mean width was declining from March onwards: 10.3 ±0.4 deg(Jan.8-Feb.23), 9.9 ±0.3 deg (March 3 – April 13), 9.5 ±0.3 (April 14 – May 22). 9.2 ±0.5 (May 23-June 26). It then recovered slightly and remained at 9.5 ±0.3 (June 28-Sep.4). Both N and S edges shifted, but probably more the S edge (which was squeezed not only by the large flakes, but also by the STB Spectre).

For the GRS, 1^o longitude = 1165 km; 1^o latitude = 1122 km. So in early and late 2019, the GRS measured ~14.0^o x 9.6^o = 138 x 10^6 km^2. In June, it measured ~12.6^o x 9.2^o = 119 x 10^6 km^2, a loss of 14% of its area.

The left-hand two panels of Fig.30 show the same from 2011 to 2019. Historical data show that the width reduced gradually until 2013, when the GRS shrank as a whole, and the width declined to 9.4 deg [refs.7&8]. It was even narrower at the end of 2014, ~9 deg wide, possibly even smaller than in 2019 June. We note that, although the visible outline normally coincides with the edge of the rapid circulation, it may not always do so, so our measurements do not determine whether the GRS circulation shrank in 2019. It is possible that the circulation did not change much even though the red, methane-bright cloud cover was disrupted. This will be discussed in Section 8.

Around the N edge of the GRS, on May 25-29, a thin red methane-bright line connected the large flake at the p. end (no.6b) to the new flake on the N side that grew into the large one at the f. end (no.7a) (Figs.18 & 19). This tenuous line, running between the borders of the GRS and the RSH, was still distinct in late June, but now 'warm greyish' (Fig.20). Also, 'warm grey' shading developed in the RSH and in the STropZ just p. it, becoming notably darkened by mid-June. The nature of these shadings is unclear though they could represent residual material from the flakes and collar that had been wound repeatedly around the GRS. In July and August (Figs.21-23) the tenuous line was still present but the space inside it was turning light brown, producing a 'cocoon' around the GRS, which persisted in some form until the end of the apparition (Fig.26).

As the GRS had shrunk, we speculated that the thin line around the N side might mark its original outline; but this was not the case. Latitude measurements show that the thin line was further north than the original GRS north edge (Fig.31). The outline of the RSH, which marks the course of the SEBs jet around the GRS, had not moved south; this suggested that the circulation of the GRS might not have changed dramatically (as Andy Casely and Clif Ashcraft noted).

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6. Discussion

6.1. Dynamics of flaking events

The consistent timing of the events makes it clear that the red, methane-bright 'flakes' or 'blades' are induced at the f. end of the GRS by rings (vortices) from the SEBs jet that enter the RSH at its p. end. Sometimes the disturbance tracks round the S edge of the GRS to produce a flake at the p. end as well. The typical timing is indicated in Fig.6.

Being red and methane-bright, like the GRS itself, it is reasonable to suppose that the flakes are material from the GRS, or at least its upper layers. So far as we can tell, the flakes appear simultaneously in RGB and the methane band. (This is shown in sets of images covering the origin of the flakes on April 16 (Fig.11) and May 14-15 (Fig.14) and June 20 (Fig.20). Often the methane image only shows a bright bulge where the flake is attached to the GRS, because of the limited resolution in that waveband, but it supports the view that this is material coming from the GRS, not emerging from elsewhere. Nevertheless, these disruptions could be quite superficial, only drawing material out from the red upper cloud deck of the GRS while not affecting its underlying circulation.

We have proposed that the flakes are created as sketched in Fig.14 (lower panel). As the SEBs ring or its decaying remnant travels around the rim of the GRS, its anticyclonic circulation reduces the wind speed of the periphery of the GRS at the point of contact, and draws material out from the GRS behind the ring. In 2019, we never had quite sufficient temporal and spatial resolution to visualise this process fully. But in a hi-res Cassini sequence [see Part II], a flake was induced exactly as proposed in the model in Fig.14.

Once created, the flake is then advected by the regional currents, westward along the SEBs and/or eastward around the south rim of the GRS. Material taking the latter course can then emerge as a flake at the p. end, and continue in two possible directions: continuing to circulate around the GRS (which may be the origin of the narrow line that developed in the RSH, and of subsequent flakes), or travelling eastward along the STropB. Red flake material appeared to be intermingled with grey or brown material of the SEB(S) f. the GRS and the STropB p. the GRS, and in the latter case, contributed to forming red, methane-bright rings.

Despite the clear link with incoming SEBs rings, the size of the flakes produced was unpredictable. They had modest sizes early in the year, then three large ones were produced in April and May which later emerged at the p. end of the GRS as well; but a few incoming rings produced little or no visible flaking.

It is possible that the STB Spectre affected the flaking events. It was passing the GRS from 2019 May to Oct., so we suspected that it could have enhanced the major east-end flaking events in May. Because its winds are stronger than the usual jetstreams, it must have altered the meridional wind gradient across the southern periphery of the GRS; the STBn jet is normally squeezed around the S edge of the GRS and the JunoCam images showed the STB Spectre distorted similarly (Fig.22). However, it would not have been responsible for the flaking events in April or earlier.

It was remarkable that these flaking events were observed by Juno at the first three perijoves since solar conjunction, and by amateurs in almost every month of the year, whereas they had previously been little known. In Part II, we will consider several possible, non-exclusive reasons why these flaking events have become so frequent in 2019: (i) the improved quality of amateur observations since 2011; (ii) the increased number of SEBs jet rings in 2019; (iii) the historically small size of the GRS, which may have made it more susceptible to disruption.

Part II will consist of:
Section 6: Discussion (continued)
Appendix 1: Previous records of SEBs rings and GRS flakes
Appendix 2: Pro-Am interaction

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