[2016 Nov.9]

Jupiter in 2015/16: Final report

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Appendix 1: The SEBs jet in 2016: wave motions and super-fast motions

(John Rogers & Gianluigi Adamoli)

The SEBs jet is the fastest retrograding jetstream on the planet. Evidence from various sources indicates a peak wind speed of DL2 = +134 deg/month [refs.17 & 26]. It often carries visible vortices with slightly slower speed, as was also the case in 2015/16 (see main text). (In this Appendix, contrary to the convention elsewhere on the planet, ‘faster’ and ‘slower’ refer to speeds in the retrograding direction, i.e. positive DL2.)

We recently reported that the SEBs jet often carries regular waves, of a prevously unknown type, which retrograde much more slowly than the jet itself, although they are at the same latitude [ref.17]. These waves have been shown in amateur images in several recent apparitions, from 2010 to 2014/15 (Fig.X0). We found that the speed of the waves relative to the jet peak is proportional to their wavelength, extrapolating to zero wavelength at the jet peak speed (DL2 +134 deg/mth) [ref.17]. This ‘dispersion relation’ holds for wavelengths of 4.5° to 10° longitude, which have been recorded in very different conditions of the SEB, before and during and after the SEB Revival in 2010-11.

In 2016, from Feb. onwards, after all the distinct vortices had disappeared, several prominent wave-trains again developed on the SEBs, with wavelengths of 4° to 6.5° longitude [e.g. Figs.12 & 17]. They remained visible, most of the time, at least until June. However, they were not always present and individual wave-trains changed rapidly. We therefore undertook careful analysis of some of the most regular examples. Such waves are not always included in the routine JUPOS work, so GA made new measurements. For such closely-spaced features, it is challenging to obtain measurements of sufficient frequency and accuracy to establish drift rates and avoid aliasing.

The results were very clear (Table X1 and Figs.X2 & X3). All the wave-trains were retrograding much more slowly than the normal jet peak, having speeds of DL2 = +68 to +95 deg/mth.

Table X1: SEBs wave-trains in 2016.

	Dates 2016	DL2	+/-	u3	Spacing	+/-	Lat.(S)	+/-	N	Amplitude	+/-
		(deg/mth)		(m/s)	(deg)		(deg)			(deg)	
E	Mar 10-16	85,0	4,0	-42,4	4,7	0,3	-20,0	0,2	7	1,05	0,10
F	Mar 10-16	95,0	4,1	-46,9	4,0	0,4	-20,2	0,1	4	0,46	0,12
A	Apr 17-23	88,2	4,8	-43,8	4,9	0,3	-19,8		5		
B	Apr 20-26	87,9	4,6	-43,7	5,0	0,5	-19,8	0,3	8	0,55	0,10
B	Apr 27-May 10	83,3	3,9	-41,6	4,8	0,2	-19,8	0,2	12	0,94	0,10
C	Apr 15-22	80,7	2,0	-40,4	5,0	0,2	-19,6	0,3	6	1,03	0,40
C	Apr 24-29	89,2	8,3	-44,3	4,8	1,0	-19,7	0,4	8	1,09	0,39
D	Apr 24-May 6	68,0	4,0	-34,6	6,5	0,8	-19,7	0,2	15		
H1	May 29-Jun15	78,3	2,0	-39,3	5,7	0,13	-20,0	0,11	5		
H2	May 29-Jun15	72,0	1,2	-36,5	6,2	0,21	-20,1	0,15	4		
							-19,87				
	Uncertainties are standard deviations. Amplitude is peak-to-peak.										

Wave-trains are identified by letter in the first column.

When the speeds were plotted against the wavelengths, they agreed well with the correlation established for the 2010-2015 data, and extended the linear correlation to shorter wavelengths, nicely confirming the validity of this dispersion relation over multiple years and conditions of the SEB. We note that some of the new values lie slightly to the right of the previous mean line, i.e. they are slightly faster (by ~5 deg/month), which is interesting in view of the detection of exceptionally fast peak jet speed in 2016 (see below); however the difference in wave speeds is unlikely to be significant.

The centre latitude of the waves was 19.8 (±0.2) °S, i.e. at the peak of the SEBs jet. The troughs had a mean latitude of 19.3 (±0.33) °S, and the peaks, 20.2 (±0.16) °S. The peak-to-peak amplitudes varied from 0.46 to 1.1 deg. latitude (**Table X1**), representing 11-22% of the wavelength in degrees longitude, similar to the range for wave-trains from 2010-2015.

The wave-trains arose in the sector L2 ~ 40-90, which was downstream from more chaotic SEBs, and alongside several mini-barges. Part of the variability of the wave-trains may have been due to interactions with adjacent features as they passed: the mini-barges in the SEB, and the dark streaks on SEB(SS). But a major contribution came from features embedded in the wave-trains themselves which were retrograding very much faster!

We found compelling evidence for concurrent, very rapid retrograding speeds, of DL2 ~ +150 deg/mth. Three individual white spots or bays, plus one pair, were found to have speeds in this range [Table X2 & Fig.X2]. Three of them are designated superfast spots (SFS) f, b and c, as they were initially just bays within more slowly-retrograding wave-trains F, B and C; however they were also visually distinctive for at least part of their lifetimes. The fourth (earliest) is named SFS-g.

Table X2: Super-fast white spots on SEBs in 2016.

Name	Dates	Description	DL2	Lat.	n
g	Mar 5 – 18	Tiny w.s. f. wavetrain F	142,5	-20,4	13
f	Mar 8-13	Pair of bays in wave-train F	149,4	-20,2	5
b	Apr 20-27	W.s. in wave-train B	151,5	-19,9	6
c	Apr 21 – May 7	W.s. in wave-train C	141,8	-19,8	16
		Mean:	146,3	-20,1	
		SD:	4,9	0,3	

SFS-g: An almost point-like white spot. It arrived at the RSH on March 19 [identified on Fig.12].
SFS-f: A pair of bays, initially part of wave-train F, but then emerging as a bright pair of bays at the f. end as the rest of wave-train F subsided to low amplitude.
Although the measurements for each rapidly-retrograding bay always coincided with troughs (bays) in wave-train F, they consistently showed a relative shift over 10-hour intervals, and these points all connected up to reveal a more rapidly retrograding spot, which must have 'hopped' successively from one trough to the next. Lest this account should seem far-fetched, we showed exactly the same behaviour in wave-train B (see below), and in 2012 (see below), and also at the start of the SEB Revival in 2010 (although that was for dark spots rather than bright spots).
SFS-b: A specially bright little white spot, always observed in a bay that appeared to be part of the wave-train B, and yet when plotted separately it had almost twice the speed of those waves. As with wave-train F, it must have 'hopped' from each bay of the wave-train to the next very rapidly, as we found no images showing it in transition. (It may have persisted for longer, as its extrapolated track coincided with successive leading bays in the wave-train, but it was no longer distinctively bright.)
SFS-c: Initially a bay in wave-train C, but as that wave-train subsided around April 27-29, it emerged as a single tiny white spot.

The mean of these 4 speeds is DL2 = +146.3 (±4.9) at 20.1 (±0.3) °S.
Also, the charts of the wave-trains showed that they were separated by gaps with a drift of ~ +150 (±6) deg/mth [Fig.X2].
As usual, we cannot tell whether this speed represents a wave phenomenon (group velocity of the wave-trains?) or a physical speed (peak of the jet at a deeper level?).

The only other recent record of such fast speeds was in **late 2012** [ref.27]. Then, we reported 6 tiny white spots with DL2 = +141 to +165 (mean = +150.8), some of them being embedded in wave-trains. In the one case that was measured (manually), it seemed likely that the whole wave-train shared the very fast speed of the white spot (w7) [ref.27]. However, that speed was only robust for the white spot; so we have re-measured those images in WinJUPOS, and find that while the rapid speed of the white spot is confirmed (DL2 = +146.4), the adjacent waves were moving more slowly, with DL2 ~ +62 to +89 [Fig.X2]. Thus, these features in 2012 behaved just like the ones we here report in 2016. On the other hand, the measurements for the waves do not fit constant drift rates as well as in 2016. As indicated by lines on the chart, we speculate that the waves were themselves subject to an oscillation in phase speed; moreover, this might have been induced by a brief disturbance propagating with DL2 ~ +150! Indeed, if the phase speed and wavelength are estimated for the extremes of these tracks, they agree with the dispersion relation, although this cannot be established precisely.

This speed of DL2 ~ +150 is much faster than the speed which we currently take as the true jet peak, DL2 = +134 deg/mth [ref. 17 & 26]. There is no precedent for this very fast speed, except when a S. Tropical Disturbance or Dislocation was present.* Does it represent a true wind speed, and if so, has the jet accelerated?

*[*Footnote:* from Ref.27: Up to 2012: "The last time such a rapid speed was detected was in 1993 (when we tracked one spot with DL2 = +145; BAA unpublished report). Since then the mean speed has never been greater than +131 deg/mth (up to 2011, inc. unpublished JUPOS data). The fastest SEBs peak speed in spacecraft ZWPs was +133 deg/mth from New Horizons."]

Given that the principal super-fast features were isolated white spots, they seem likely to have been physical features, not waves. On the ZDP [Fig.5] they fall on the same line as the larger, slower vortices, suggesting that these spots are all tracing the same underlying ZWP. As the super-fast spots were very small, and usually embedded in slower-moving wave-trains, they would have been overlooked until recent years; moreover, so far they have only been observed when there are no distinct vortices on the same sector of the jet*, which is not the usual situation.

*[*Footnote: Why* there were no retrograding vortices is unclear, given that the post-GRS rifting was as vigorous as usual from autumn 2011 to spring 2016, with only a brief hiatus in early 2015. The lack of vortices may also have allowed the concurrent slow waves to develop; however this was not the case in 2014/15 when typical vortices on the jet co-existed with, and perhaps excited, the slow wave-trains.]

It seems unlikely that the super-fast speeds represent a real change in the jet, given that we have observed them in 2012 and 2016 whereas in the intervening years there were vortices retrograding with their normal speed and a normal jet peak speed. We therefore suggest that the jet really does have a peak speed of ~+150 deg/mth, perhaps not at cloud-top level but deeper down. The gaps that delimited the slow-moving wave-train, also moving with DL2 ~ +150, mght represent disturbances on that deeper jet. As in the case of the prograde jets on NEBs and NTBs, a permanent super-fast deep jet may only occasionally produce disturbances that can be seen at cloud-top level.

References for Appendix 1:

17. Rogers, JH, Fletcher, LN, Adamoli, G, Jacquesson M, Vedovato M & Orton, GS (2016). 'A dispersive wave pattern on Jupiter's fastest retrograde jet at 20ºS.' Icarus 277 (2016) 354–369. http://dx.doi.org/10.1016/j.icarus.2016.05.028 *Also preprint at:* https://arxiv.org/abs/1605.07883 & https://britastro.org/node/7718

26. Rogers J & Mettig H-J (2008), 'Jupiter in 2007: Final Numerical Report.' http://www.britastro.org/jupiter/2007report20.htm

27. Rogers J, Adamoli G & Vedovato M (2015), Jupiter in 2012/13, Report no.12: 'The SEBs jet in 2012/13.' http://www.britastro.org/jupiter/2012_13report12.htm.

Figures for Appendix 1:

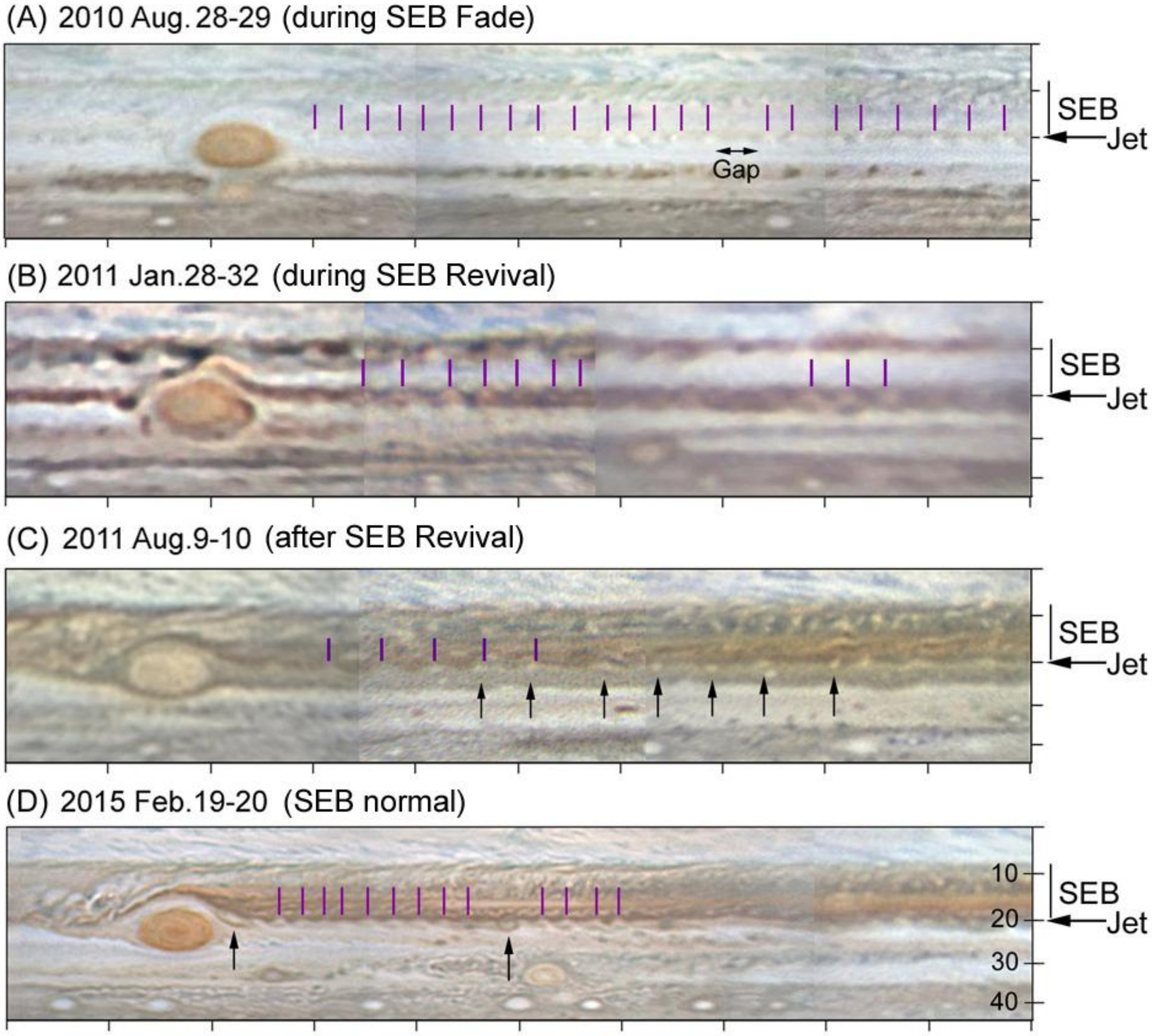

Fig.X0. Maps of the SEB with wave-trains in four different conditions of the SEB: before, during and after the SEB Revival of 2010-11. Adapted from [ref.17]. All maps were made by M. Vedovato from aamteur images. Full details were given in our on-line reports for each apparition. Each map covers 200º longitude with gradations at 20º intervals. Rows of purple marks above the SEBs indicate the slow-moving wave-train. Black arrows below the SEBs indicate features moving at or near full jet speed.

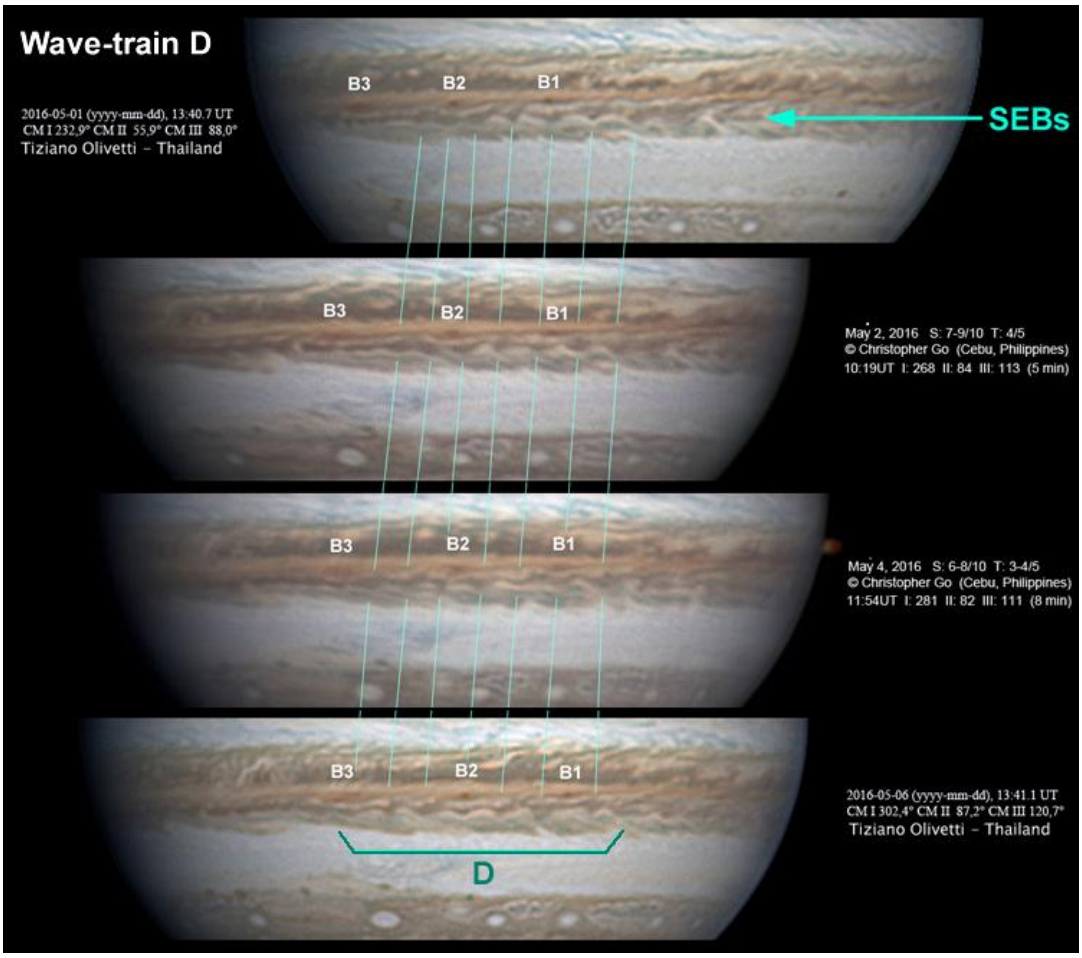

Fig.X1. V-hi-res images of wave-train D, May 1-6. The wave-crests are tracked as in **Fig.X2**. Note the variations in form of the individual waves. They are passing three barges, labelled thus: B3 is the merged barge, fading away at this time; B2 is a new mini-barge; B1 is another incipient mini-barge but did not persist.

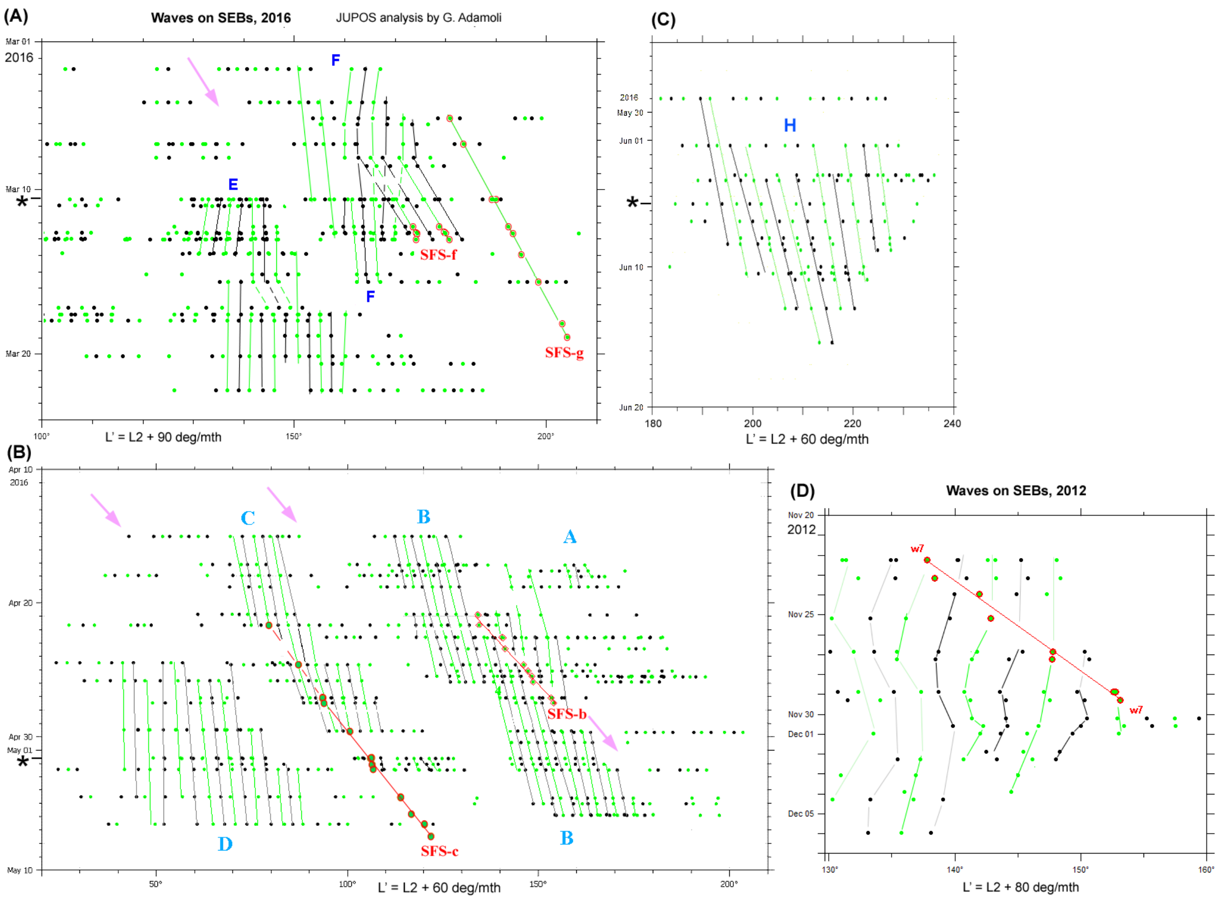

Fig.X2. JUPOS charts of several wave-trains on the SEBs (all produced by GA). Note that longitude systems with several different drift rates are used; asterisks indicate when they are equal to L2. Black points, dark humps (wave-crests); green points, light bays (wave-troughs); red-circled points, rapidly retrograding white spots. In addition to these documented 'super-fast spots', there are hints of very brief super-fast speeds elsewhere on the charts. Magenta arrows indicate gaps between wave-trains propagating with the super-fast speed of DL2 ~ +150 deg/mth.
(A) Wave-trains E,F,G in 2016 March. (B) Wave-trains A to D in 2016 April-May. (C) Wave-train H in 2016 June. (D) Wave-train in 2012 Nov-Dec., plotted on a larger scale than the other panels.
Lines trace the tracks of the wave crests and troughs; fainter lines are more speculative.

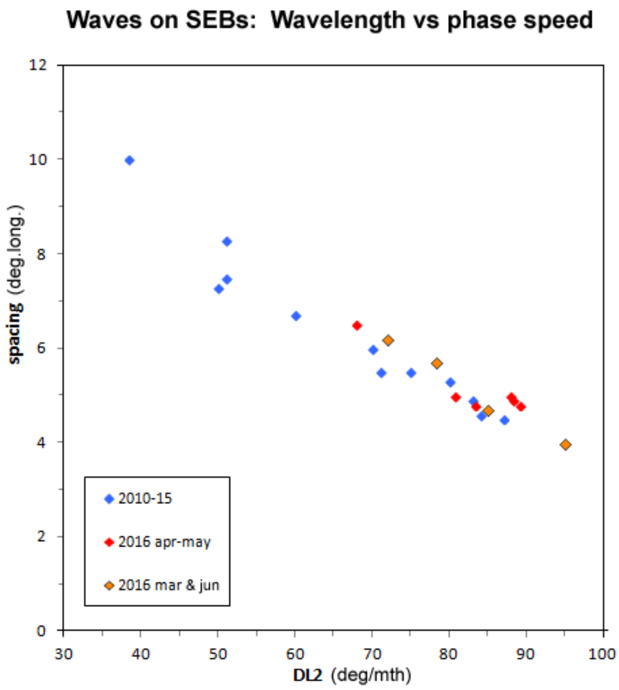

Fig.X3. Chart of wavelength vs speed. The blue points were shown in [ref.17], from 2010-2015; the red and orange points are new from 2016. Note good agreement with the previous linear relationship.

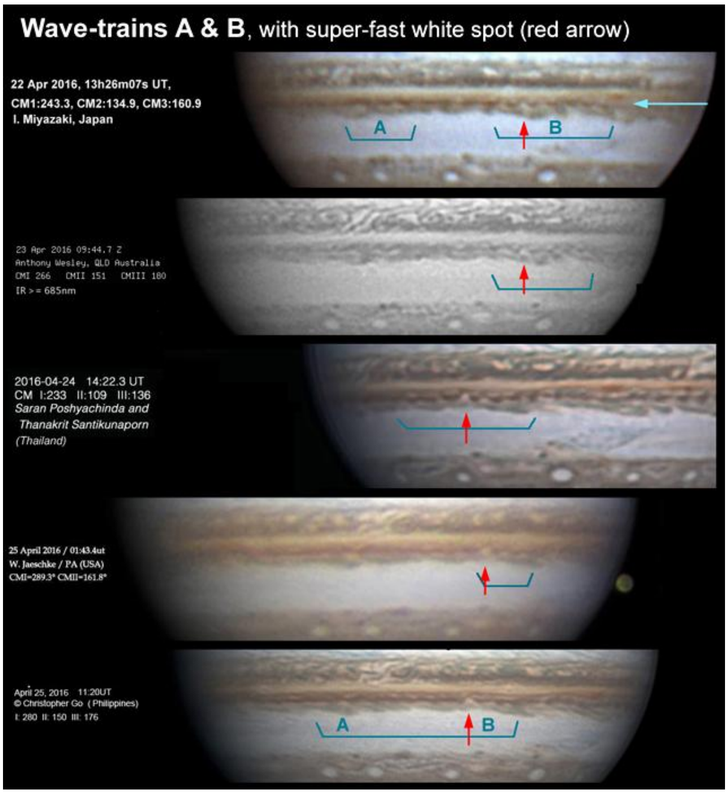

Fig.X4. Images of wave-trains A and B, April 22-25. Wave-train A is elusive until April 25 when A and B form a single long wave-train. This figure does not attempt to connect up individual waves. The red arrow indicates the super-fast white bay (b), identified as being consistently brighter than other bays. The light blue arrow at right indicates the SEBs jet.

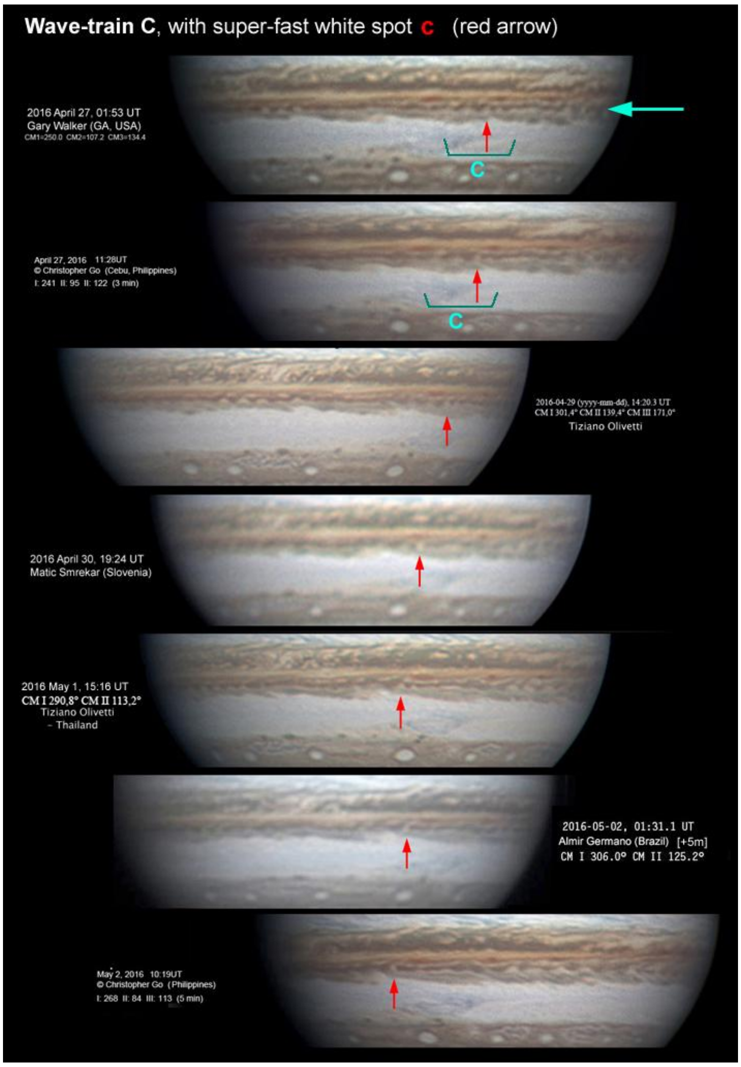

Fig.X5. Images showing a tiny super-fast white spot (c) (red arrow), which emerges from slower wave-train C. The light blue arrow at right indicates the SEBs jet.

Appendix 2: Mapping the circulation within the GRS

(Michel Jacquesson & John Rogers)

For ten years we have been measuring the internal circulation of the GRS by tracking single dark streaks which are sometimes recorded near its periphery; they can be tracked around up to 3 rotations, revealing a rotation period of 3.6 to 3.8 days.
In 2015 and 2016, improved image quality has revealed smaller-scale texture within the GRS, previously only recorded by HST [refs.28-30]. Although it is close to the limit of resolution and noise, enough features can be identified over a 10-hour interval to allow the first ground-based measurements of the rotation rate at different radii.

As in our previous work, the circulation is assumed to be an elliptical projection of circular motion, so the GRS is reprojected to appear circular, and the position angles of features are measured in images taken on successive planetary rotations, ~10 hours apart (e.g. **Fig.X6**). In the present work, all images were mapped using equirectangular projection, before being stretched in the N-S dimension so as to appear circular by eye. As the features are close to the noise level, some features could be noise artefacts, or distorted by real changes between the images. Nevertheless, the ensemble gives consistent results. Uncertainties are estimated as follows. The angular displacements are typically ±2 deg, so angular velocities are ±10 deg/day. Radial measurements are ~±12%, and absolute scale to ±5% (uncomfortably large, but possibly including real short-term changes in the dimensions of the GRS). The map projection creates a 6% difference in scale between the north and south edges of the GRS – although this can perhaps be regarded as a small distortion in our assumption of circular motion.

The measurements in 2015 and 2016 give almost identical results, as shown in **Fig.X7** and **Table X3**. The circulation is indistinguishable from solid-body rotation from 0.45 to 0.95 x outer visible radius. The mean rotation rate is 105 (±16) deg/day, implying a rotation period of 3.4 (±0.5) days. The absolute speed (referred to the minor axis) is thus proportional to radius, up to 150 (±16) m/s (mean of 16 points between 0.87 and 0.97x outer radius). [*See Footnote*.]

Table X3. Measured parameters of GRS circulation

	2015	+/-SD	**2016**	+/-SD
No. of dates	7		5	
Outer radius R (km)	8167	333	8288	402
Range for solid-body rotation (xR)	<0,6 to 0,97		0,45 to 0,9	
Mean angular speed (deg/day)	106	16	105	16
Implied rotation period (days)	3,4	0,5	3,4	0,5
Implied rotation period (hours)	81,8	12	82,5	13
Peak angular speed (m/s)	149,4	10,1	150,5	26,8
--at radius (xR)	0,87 to 0,97		0,87 to 0,90	
--(no. of points)	11		5	

[*Footnote:* Our previous measurements for the GRS rotation, up to 2014, were for dark streaks near the periphery, more conspicuous and long-lived than most of the features tracked here. The present measurements included five streaks of this type from 2014 Nov.8 to 2015 April 13, with a mean rotation rate of 95 (±10) deg/day, implying a rotation period of 3.8 (±0.4) days, the same as we observed previously and slower than for most smaller features. They also included two such streaks on 2016 March 30 and April 23, which had faster rotation rates similar to the smaller features; but given the uncertainties, we do not think this shows any definite change in their behaviour.]

These results differ from spacecraft-derived maps of the GRS flow field up to 2006 (the latter having been analysed in Ref.28), which showed a quiescent or chaotic central region, with a speed gradient that was steeper than solid-body rotation leading up to a high-speed collar near the outer rim. It is possible that the speed profile has changed since then with the shrinkage of the GRS. Our present results are more similar to those derived from HST images on 2014 April 21 (Refs.29 & 30), which implied periods of 3.0 to 3.8 days between 0.5-0.97x outer radius; the typical rotational velocity was ~150 m/s, with a period of ~3.2 days. The present results do not have sufficient precision to establish any definite changes, but we can conclude that the internal flow field has indeed been recorded in our ground-based images; it shows approximate solid-body rotation in the outer half of the GRS; and there has been no significant change in the wind speeds since early 2014, as the size of the GRS has also remained approximately constant over that time.

References for Appendix 2:

28. Asay-Davis, X.S., Marcus, P., Wong, M.H., de Pater I.(2009), 'Jupiter's shrinking Great Red Spot and steady Oval BA: Velocity measurements with the 'Advection Corrected Correlation Image Velocimetry' automated cloud-tracking method.' Icarus 203, 164-188.

29. Simon AA, Wong MH, Rogers JH, Orton GS, de Pater I, Asay-Davis X, Carlson RW & Marcus PS. (2014) 'Dramatic Change In Jupiter's Great Red Spot From Spacecraft Observations' *Astrophysical Journal Letters,* 797:L31-L34 (2014 Dec.20) doi:10.1088/2041-8205/797/2/L31.

30. Rogers JH (2016 Nov.). 'The circulation of the GRS, 2009-2014: preliminary analysis of HST images.' https://britastro.org/node/8262

Figures for Appendix 2:

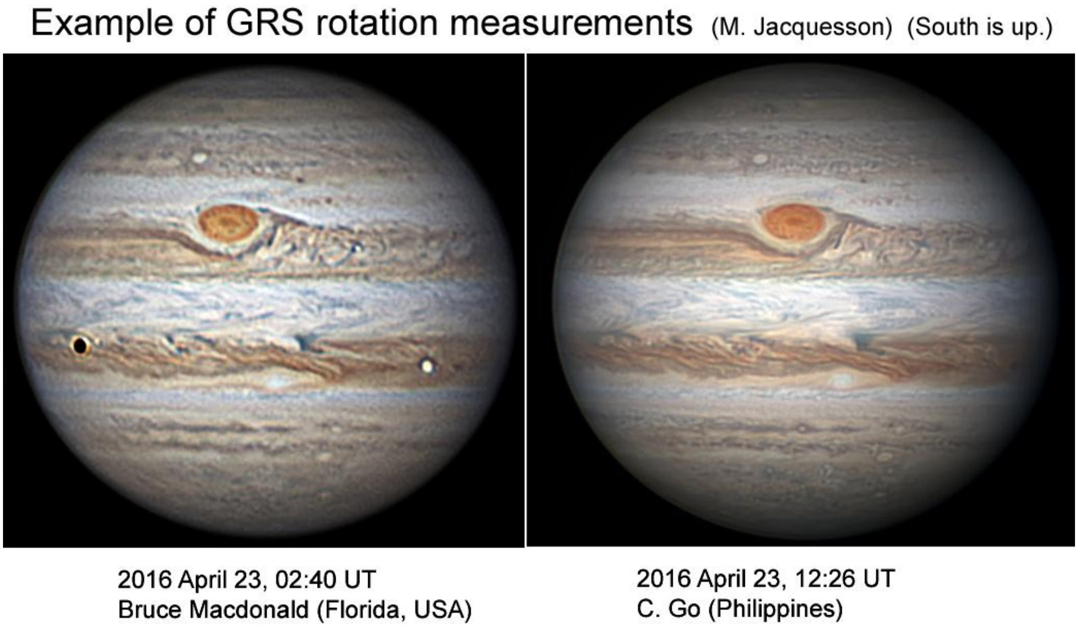

Figure X6. Example of reprojection and tracking of features within the GRS.
[Top panels; continued on next page]

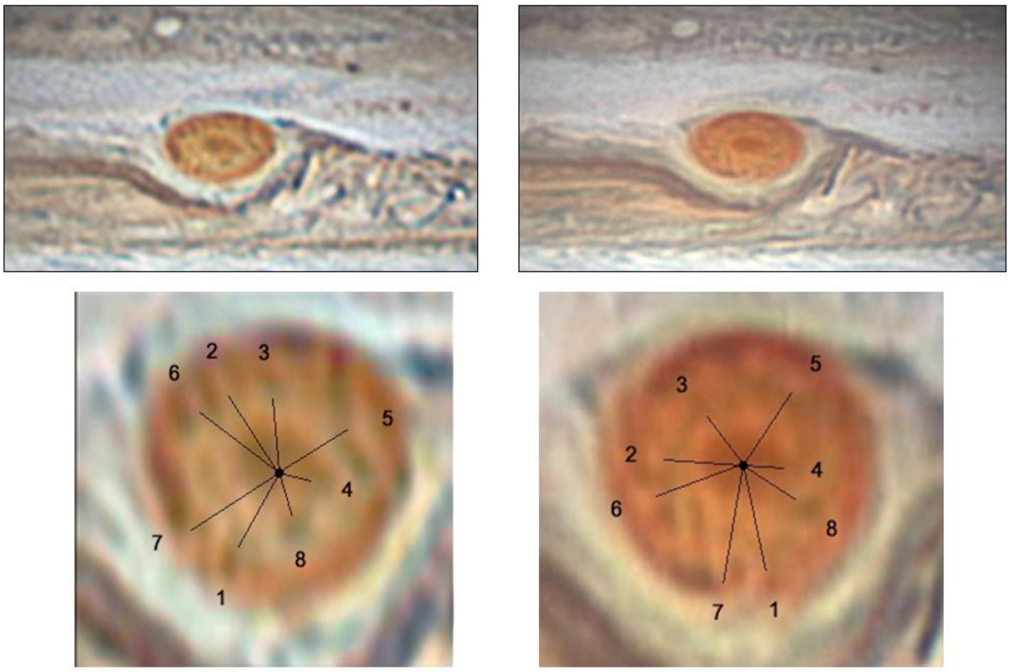

Figure X6. Example of reprojection and tracking of features within the GRS [*continued*].

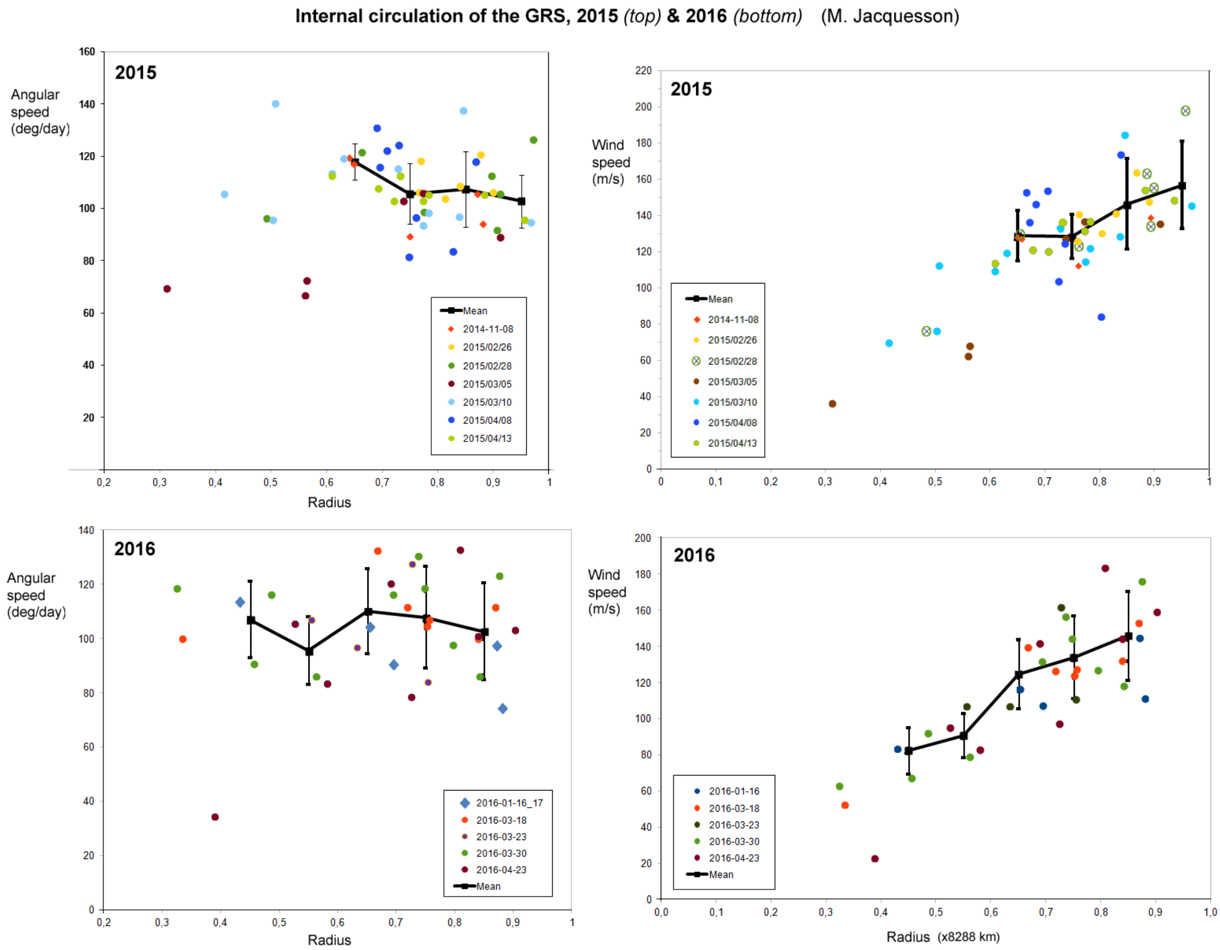

Figure X7. Deduced rotation rate and wind speed as a function of radius within the GRS.

Appendix 3: Juno at perijove-1: a global survey of Jupiter

(John Rogers)

The 2016 apparition was unusually extended as the Juno spacecraft, which entered orbit around Jupiter on July 5, made its first operational perijove on August 27, just a month before solar conjunction on Sep.26. Thus the planet was well mapped on August 26-28, both by ground-based amateurs and by Juno's 'public outreach' camera, JunoCam.*

**Footnote:* The JunoCam images are specifically intended for public involvement and we thank Dr Candice Hansen (principal investigator) and Dr Glenn Orton (contact for amateurs) for the opportunity to work with these images; and amateur Gerald Eichstädt, who has processed and projected the numerous JunoCam images and converted them into maps. For more about amateur involvement with the Juno mission, see [Refs.30-32].

Three amateur observers – Phil Miles, Anthony Wesley and Isao Miyazaki – continued observing around those dates; Miles and Wesley, observing at adjacent sites in Queensland, Australia, were taking infrared images well before sunset. A map made from Miles' images is shown in **Fig.X8**. Meanwhile, JunoCam was taking images at half-hour intervals in the days before and after perijove, nicknamed 'marble movies'. From the last ten hours of imaging which ended 2 hrs before perijove, and the first ten hours which started 6.5 hours after perijove, a high-quality map was produced (**Fig.X9).** (These maps show fair agreement with a predictive map that was posted in our Report no.10.)

Here follows a summary of features which have been described in our apparition report, labelled on the JunoCam map, to give an update on the development of these atmospheric features. A version of this was previously posted [Ref.32] with the individual marble-movie images. (It does not cover the fascinating features in the polar regions which are inaccessible to ground-based observers: see Ref.X-5.)

Northern hemisphere:
There have been no substantial changes over the past half-year. The map shows the four anticyclonic ovals in the NNTZ (WS-6 and LRS-1 which both contain an orange annulus, and WS-4 and -8 which are white); many vortices on the NNTBs jet; the major FFR in the NNTB (L3 = 319-350); and the rifted region in the NTB (L3 ~ 248-308). The principal spots along the NEBn are also unchanged: four small 'barges' (labelled B-1 to B-4), and White Spot Z.

Southern hemisphere:
In the SEB following the GRS, there is normal rift activity. Oval BA (strongly reddish) is approaching the GRS. The small dark patch following it seems, at last, to have rounded up to form a quiescent small dark brown barge.

There is an unusually dense outbreak of small dark spots on the prograding SSTBn jet, between a large FFR in the SSTB (f. oval A5) and the 'STB Ghost', where we have observed such spots to recirculate into the STZ. (This region was imaged by JunoCam at perijove, showing two of the spots near the point of recirculation.)

The most notable changes are affecting the S.S. Temperate AWOs. Two small ones appear to be merging in these images (at L3 = 260); such small-scale events are not uncommon and we observed one earlier this year. However, the nine numbered AWOs are very stable, and yet two of those – A0 and A8 – have rapidly converged to only 9° apart. They have always been smaller than most, while their neighbour, A1, has become the largest. We are therefore looking for A8 and A0 to merge with each other, and possibly with A1 as well, in the coming months, perhaps after they have passed oval BA. In addition, a cyclonic white oblong developed in August between A3 and A4, and can be expected to expand. These phenomena will no doubt perturb the relative drifts of the AWOs.

References for Appendix 3:

30. Rogers JH (2016 August), 'Jupiter and the Juno mission: the amateur's contribution.' J.Brit.Astron.Assoc. 126 (no.4), 197-200 [& cover]. https://www.britastro.org/node/7957.

31. JunoCam web page: https://www.missionjuno.swri.edu/junocam.

32. BAA Jupiter Section web page, 'Results from Juno': https://www.britastro.org/node/7982.

Figures for Appendix 3:

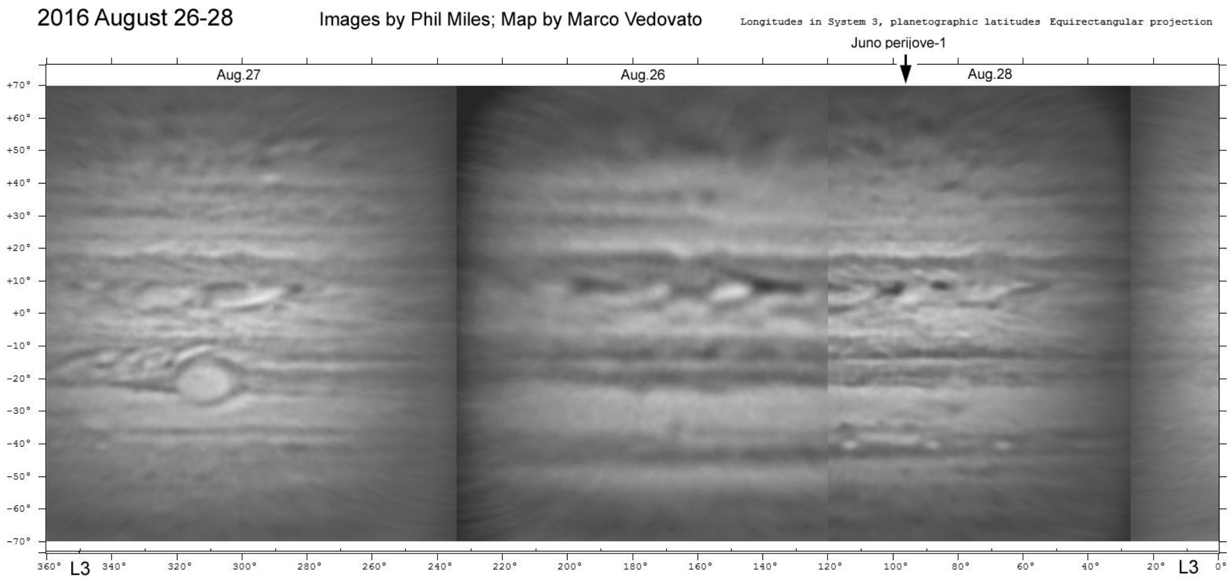

Figure X8. Map of the planet from images by Phil Miles, 2016 August 26-28 (map made by Marco Vedovato, JUPOS team).

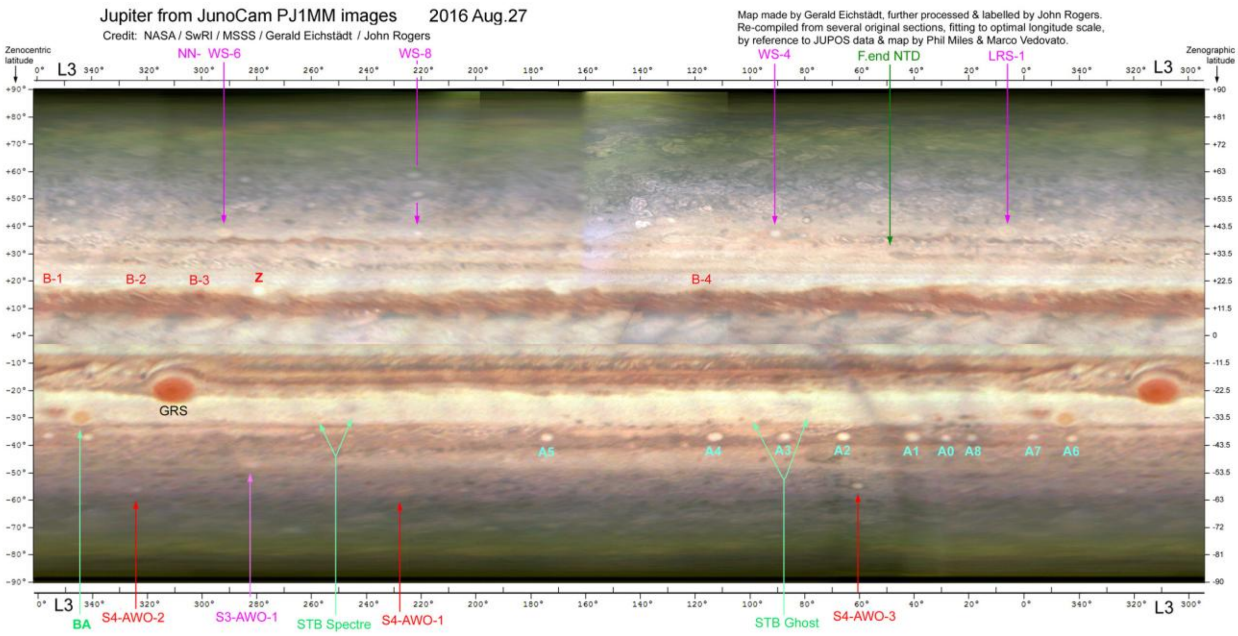

Figure X9. Map of the planet from JunoCam images, 2016 August 27-28.
This map is mainly due to Gerald Eichstädt, from images taken just before and after perijove-1. The northern hemisphere is from inbound images from 01:15 to 10:45 (UTC at the spacecraft), and the southern hemisphere is from outbound images from Aug.27, 19:15 to Aug.28, 04:45. The map has been generated by collaboration of many amateurs using the data from NASA's Juno team. Gerald Eichstädt processed and projected the JunoCam images and converted them into maps. Because images of this oblate planet taken from such high latitudes and phase angles had never before been used to make a map, it was difficult to achieve accurate coordinates, so I checked the longitude scale of the map by reference to amateur data: charts from the JUPOS team up to August, and the map in **Fig.X8**. The images by Miles and Wesley were essential for accurate alignment. Gerald and I then re-compiled the map and adjusted the colours and intensities to enhance visibility of features. The scale is in L3; for L2, subtract 60 degrees. Positions are thought to be accurate to ±3 degrees. The major features are labelled.
This map has also been posted on the JunoCam and BAA web pages [refs.31 & 32]
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