The circulation of the GRS, 2009-2014: preliminary analysis of HST images

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Summary

In early 2014, our measurements on amateur images of the Great Red Spot (GRS) showed that its circulation period had decreased to an exceptionally short 3.6 days, which was largely due to shrinkage of the GRS, but possibly also due to acceleration of the wind speed [Ref.1]. Imaging by the Hubble Space Telescope (HST) was obtained on 2014 April 21 to investigate this further, and the wind speed was indeed found to have increased to a maximum of ~150 m/s, although it was not quantitated in detail [Ref.11]. Here, I report manual measurements of the GRS circulation from HST images taken in 2009 Sep. and 2012 Sep. as well as 2014 April, and offer a comparison with other HST and ground-based results.

In order to obtain a simple parametrisation of the GRS circulation, and compatible with simple image projection techniques, the GRS circulation is approximated as an elliptical projection of circular motion, and angular displacements are measured. Therefore the results are presented primarily in terms of the implied rotation periods, with wind speeds derived therefrom.

The results confirm that amateur images can track the circulating features accurately, though they do not always capture the fastest wind speeds. HST and ground-based measurements gave exactly the same rotation period for a large streak in 2012, but other features in the HST images rotated faster, indicating that the rapid rotation seen in 2014 had actually begun earlier.

In all 3 sets of HST data, the deduced rotation period did not vary significantly with radius from r~6300-7400 km, at least. Streaks at larger radius and (in 2014) at smaller radius had longer rotation periods. Between 2009 Sep. and 2014 April, the implied rotation period decreased significantly (from 91 to 79 hours). This was mainly due to the physical shrinkage of the GRS. The peak wind speeds showed no significant increase: 147 m/s in 2009, 150 m/s in 2012, 150 m/s in 2012. However, these speeds were significantly faster than those previously reported in 2006.

The consistency of the 2009 parameters with the long-term trend, despite an SEB Fade at the time, contradicts the prevailing view that influx of vortices on the retrograde SEBs jet sustains the circulation of the GRS. Likewise the unchanged speed in 2014, when spots on the STBn jet were impinging on the GRS, shows that these spots do not affect the circulation either.

Introduction

In recent years it has been possible to measure the internal circulation of the GRS from amateur images, at favourable times when sufficiently large and persistent streaks have been visible within it. We have reported measurements of the circulation period in 2005 (4.7 days) [ref.12], 2006 (4.5 days) [ref.2], 2012 (4.0 days) [ref.3], and 2014 (3.6 days) [ref.1]. These have shown that the circulation period has decreased approx. in proportion to the long-term shrinkage in the length (major axis) of the GRS, implying approx. constant wind speeds, until 2014, when the shrinkage has gone beyond the long-term trend and the circulation period has speeded up even more, with an apparent increase in wind speeds. Ground-based images may not give conclusive measurements of these parameters, given the limited resolution and the possibility of not detecting the most rapidly moving features. Therefore, I have turned to images from the Hubble Space Telescope (HST) to provide higher resolution, as has already been done by X. Asay-Davis et al.[ref.4] for images in 2006, which confirmed our ground-based measurements. I report measurements on existing HST image sets from 2009 Sep.22 and 2012 Sep.20, and from 2014 April 21.

Observations and analysis

The images on 2009 Sep.22 were taken to follow up the 'Bird Strike' impact [ref.5]. They were part of a series covering the whole planet in various wavelengths from 2009 Sep.18-23, but only two images ~10 hrs apart in red light on Sep.22 covered the GRS on successive rotations. The raw images were reprojected as described on Fig.1.

The images on 2012 Sep.20 were taken during the jovian Transit of Venus [ref.6], all in near-IR (763 nm) and UV, and included images of the GRS on 3 successive rotations ~10 hours apart. The images were provided by Marco Vedovato (after correction for the HST distortion) and reprojected as described on Fig.2.

The images on 2014 April 21 was obtained at short notice using Director's Discretionary Time, specifically to investigate the GRS circulation [refs.10 & 11]. They covered two successive rotations in a full range of wavelengths. The raw images were reprojected as described on Fig.3. Unfortunately, the shadow of Ganymede fell on the GRS in the second image set. However, by high-pass filtering in Adobe Photoshop to extract detail within the penumbra, and combining two images taken 17 minutes apart so the shadow had moved, it was possible to identify features over most of the GRS.

Red-light images were used for measurement, and colour images (exactly superimposed) were used to identify the outline of the GRS. All projections were done by eye and measurements by hand, but I don't think there are large inaccuracies. The geometric distortion inherent in raw HST images was corrected by a uniform shear. If the GRS lay over the central meridian (CM), no further adjustment was made; if not, the image was 3D-rotated in Adobe Photoshop to put the GRS on the CM. The images were then stretched in the meridional direction x1.70 (2009, 2012) or x1.65 (2014) to render the GRS circular. Rotation of the GRS by ~40-46 deg. between consecutive images allowed many tie-points to be identified. Their position angles (PA) and radii relative to the centre of the circularised red oval were measured.

The circulation was analysed in terms of angular motion, treating the GRS circulation as an elliptical projection of circular motion (as in my previous measurements on amateur images). The GRS was reprojected as a circle as described on the images, and the position angle (PA) of features within it was measured, giving angular displacements over the interval between two images. I give the results in terms of implied rotation period P (hours). (It would be more logical to give angular velocity, as we do not know if any features survived for a complete rotation, but we have hitherto used rotation periods for our ground-based reports.) Given the radius, the circumferential speed v (m/s) was also calculated. Radius and wind speed refer to this circular projection, so radius is referred to the major axis, and wind speed to the minor axis.

These measurements may have inaccuracies arising from each reprojection step. For 2009 and 2012, I estimate that the uncertainty in PA is no more than a few degrees, but the uncertainty in radius from the centre of the GRS may be up to 10%. For 2014, the uncertainty in PA is ±1 deg, so that a typical rotation period of 80 hours is ±3.5 hours. The uncertainty in radius can be estimated in that measured radii were mostly smaller in the second image than the first by 0-5% (0-300 km). (However, the features measured typically had radial widths of ~450-900 km.) So wind speeds are ±10 m/s.

This is a preliminary study, as only approximate image projections could be used. More complete and accurate results can be expected from precise projections and automated velocimetry in due course. Nevertheless, reliable averages are obtained because spots and streaks are measured all around the GRS, and the resulting values show good consistency.

Results

The images and the measured features are shown in Figures 1-3. The measurements are summarised in Figure 4 and **Table 1** (with more details in Supplementary Table 1b, at end of this file).

For 2009 and 2012, I find a radius-independent period for all but the outermost features: 92 hours or 3.8 days in 2009 (r~6000-8000 km), and 83 hours or 3.5 days in 2012 (r~6300-7400 km). Within this annulus, therefore, the wind speeds increase with radius, as shown in the chart (Fig.4A). The peak wind speed is estimated in two ways, which agree well:

(a) the average speed calculated for the three outer spots within this annulus (the 'high-speed collar');

(b) the speed which would apply to the outermost of these spots if it had the mean rotation period.

For 2009, (a) 146.9 m/s, (b) 151.4 m/s, mean 149.2 m/s;

for 2012, (a) 149.8 m/s, (b) 154.3 m/s, mean 152.1 m/s.

Likewise in 2014, there is an annulus from r ~ 6200-7000 km with notional rotation period of 77 ±3 hours (3.2 days); the mean peak speed, from r ~ 6300-7200 km, is 149.5 m/s (±8.7 m/s, SD; n=7). For this epoch I also measured some points interior to the annulus: the rotation is not quite solid-body, but has a steeper gradient and a low-speed core, though I only have a few points in the core.

Table 1. Mean speed for peak of high-speed annulus

	N	Radius range	Mean P		Mean v		Mean r		Radius of
		(km)	(hrs)	+/-SEM	(m/s)	+/-SEM	(km)	+/-SEM	red oval (km)
2009 Sep.22	3	7381-7976	**91,2**	3,6	**146,9**	5,8	7659	173	9166
2012 Sep.20	3	6948-7338	**83,7**	3,0	**149,8**	5,7	7165	115	8570
2014 Apr.21	7	6307-7143	**78,7**	2,3	**149,5**	3,3	6719	119	8130
2006 April	[*]	~7650	108		**4,5**		**124**	7	~9560

(Given the small number of measurements, these numbers are sensitive to subjective definition of the high-speed annulus; the mean radius is especially imprecise, and alternative data selections can give mean peak speeds of 149-152 m/s in each year.)

The outer edge of the high-speed collar was poorly defined as few points were measured and it is unlikely to be symmetrical. In 2009, two features at larger radius (the leading and trailing ends of a dark streak on the edge of the GRS) gave substantially longer periods (6-7 days) and lower wind speeds. In 2012, one feature at the largest radius measured (7600 km) also may have been outside the high-speed collar, as it had the longest period measured (96.6 hours or 4.0 days). (This was the leading edge of a large, comet-shaped dark grey streak, and this was the same feature that we had tracked in amateur images in the same month, likewise obtaining P = 4.0 (±0.1) days.) In 2014, there was one point (c) with v = 151 m/s at r = 7865 km, but two points further out suggesting a more rapid fall-off with radius.

Structure within the GRS in 2014

To see whether there were any systematic variations of speed around the GRS, which might indicate either internal structure or failure of the assumption of circular motion, the period was plotted against PA for all features with 5600 < r < 7100 km (Fig.4C). This revealed an anomalous group of 4 features at PA 208-243 (features ci,d,di,w6 in Fig.3), which were all associated with the strange long linear structure (item C below). Otherwise I found no systematic deviation from uniform circulation.

It was notable that the GRS had large internal disturbances, at a time when it appeared quiescent and largely isolated from its surroundings. The main features (as labelled in Fig.3) appeared to be:

(A) A locus on the p. edge where dark spots or chevrons (numbers 0-6) were apparently 'budding off' at 5-hour intervals. These dark patches defined the circulation in the N half of the GRS, with mean P = 79 (±4, SD) hours, v = 140 (±10) m/s.

(B) In a part of the Sp. quadrant, a pattern of very small spots might be an eddy; change between the images precluded tracking.

(C) A bizarre long diagonal linear structure, which persisted between the images despite rotating 41° on itself. Its outer (southern) part, abutting the dark streak (see below), was flanked by features (ci,d,di,w6), but these had P = 91-96 hours, rather slow for their radius (shown in different colours in Fig.4B&C), suggesting that the circulation was perturbed around this structure. More detailed measurements might clarify this perturbation.

(D) A large dark circumferential streak in the S half (features a,bw,c,d) (Fig.3). Its leading edge (a,bw) had P ~ 73-78 hours (within the high-speed collar), while its outer edge and trailing end (c,d) had P = 91 hours (on the outer edge of the high-speed collar). These values agree nicely with our previous ground-based measurements of P = 3.6 to 3.8 days (86-91 hours) for similar streaks in Jan-Feb. But this particular streak was short-lived; it was visible in an image by Chris Go, taken at the same time as the first HST image, but not in good ground-based images taken over the previous few days.

The overall size of the GRS diminished between the three observing epochs, in accord with the long-term trend. The length of the major axis was:
2009 Sep: HST images, 15.4 deg, 18000 km; JUPOS average, 15.8 deg, 18400 km.
2012 Sep: HST images, 14.8 deg, 17200 km; JUPOS average, 14.4 deg, 16800 km.
2014 Apr: HST images, 14.1 deg, 16440 km; JUPOS average, 13.3 deg, 15500 km.
(The HST values are my measurements on blue or UV images. The JUPOS figures were derived from an average of all JUPOS data in each month, by Michel Jacquesson.)
The HST and JUPOS values agree well, even though the GRS outline was often irregular or indistinct in 2012; so these values confirm that the length of the GRS, which was constant throughout 2009 and 2010, had begun its rapid shrinkage before 2012 Sep.

Discussion

Measuring the GRS circulation from HST and from amateur images

From the HST images in 2009, 2012 and 2014, it was possible to measure many features spaced all around the GRS. Averaging therefore minimises errors in reprojection and alignment. The deduced rotation period does not vary significantly with radius from r~6300 km to r~7400 km, at least. Within this annulus the approximation of solid-body rotation, fitted to a projection of circular motion, appears to be reasonable. As with the ground-based images, the angular motion has been measured more accurately than the radius, so it is convenient to use rotation period as a parameter to summarise the GRS circulation, in conjunction with the radius.

The 2012 images happened to be taken at the same time as we tracked the GRS rotation using amateur images [ref.3], and the same large streak was measured independently in both image sets, giving exactly the same rotation period (4.0 days). The agreement is gratifying; indeed the ground-based period is more accurate because it was derived from 3.4 complete circuits, giving a long time-base and eliminating any projection errors. On the other hand, this example confirms that ground-based imaging does not always detect the fastest wind speeds. Direct comparison was also possible in 2006, when our ground-based period [ref.2] was the same as the mean period for the fastest winds deduced independently from HST images [ref.4], probably because the streaks which we tracked in amateur images in 2006 occupied a broader range of radius within the GRS.

Full characterisation of the GRS circulation requires a spacecraft flyby, but studies by the Galileo and Cassini spacecraft were limited to snapshots so the variations could have been random short-term fluctuations. This study confirms that HST images have sufficient resolution to characterise the circulation, so more frequent monitoring by HST can address the important physical questions. We also show that amateur images can track features accurately and, although they may not always capture the fastest wind speeds, they can give clear indications of significant changes.

Changes in the circulation between 2009 and 2014

Between 2009 Sep. and 2014 April, the rotation period decreased significantly (from 91 to 79 hours, a decrease of 13%). The peak wind speed showed no significant change. The decrease in rotation period was due to the shrinkage of the GRS: the major axis decreased by 12 (±4) % over this interval. As shown in Fig.5, the trend-line for velocity against radius has progressively shifted to smaller radii, indicating contraction of the whole flow field.

Fig.5 also compares these manual measurements with the latest professional measurements, from HST images in 2006 April [ref.4] [*see Footnote*]. Despite the apparent asymmetries in 2006, the comparison is interesting. The mean peak speed in 2006 was 124 m/s at r = 7650 km, implying P = 108 hours (4.5 days, identical to our ground-based measurement). From 2006 to 2009, while the visible outline of the GRS contracted, the high-speed collar did not; instead it increased its speed from ~124 m/s to ~147 m/s. Then from 2009 to 2012 to 2014, the high-speed collar contracted along with the outline of the GRS, but the speed did not change further. This evolution does not appear to have been a response to any major external factors (as discussed below); it seems more likely to be an aspect of the intrinsic secular contraction of the GRS (Fig.6).

[*Footnote:* The 2006 profiles are adapted from X. Asay-Davis et al. [ref.4]. I have scaled the profiles on the 4 hemi-axes to match the mean peak speed on the minor axis and the mean peak radius on the major axis. This required adjustment of the E-W speeds, since the minor-axis profile showed mean peak speeds of +131 m/s on the S edge and -117 m/s on the N edge; it also showed the low-velocity core to have a mean speed of ~+5 to +10 m/s eastward, so I chose to make the adjustment by subtracting 7 m/s across the whole profile, thus making both peaks equal to the mean of 124 m/s. The scaled values are approximate because, as the authors [ref.4] noted, the flow field showed significant deviations from projected circular motion, especially outside the high-speed annulus but also within it.]

Relation to adjacent phenomena and the supply of energy to the GRS

The motivation for this project was not only to track precisely the evolution of the GRS circulation, but also to determine whether it is affected by influx of vorticity from its surroundings, particularly the STBn and SEBs jets. The prevailing hypothesis for the maintenance of the GRS is that its winds are reinforced by influx of anticyclonic vortices from the retrograde SEBs jet, particularly the mid-scale

(~3000 km scale) vortices which are distinct jetstream spots, which were being ingested by the GRS during the Voyager 1 and Cassini flybys. Sometimes, as in the late 1990s and 2012-2014, the SEBs is more chaotic with few trackable jetstream spots or none, but it may well continue to carry smaller-scale turbulence. However, the supply of visible vortices to the GRS is completely cut off in two circumstances: when a South Tropical Disturbance develops p. the GRS, or when a SEB Fade develops with cessation of large-scale convective activity in the SEB. A S.Trop.D. developed in 1979 May during the Voyager 2 approach, and has been suggested as the reason why the winds in the GRS were slightly lower during that flyby [ref.8], although this could have been just a short-term fluctuation.

In 2009 Sep., a SEB Fade was under way [ref.7]: visible convective activity ceased in May-June, the GRS appeared detached from the SEB in July, and the SEB was visibly fading by August. So our finding that the circulation period and wind speeds of the GRS were maintained in 2009 Sep., in line with its long-term trend, implies that the visible vortices on the SEBs do not contribute to its circulation on this time-scale.

Conversely in early 2014, an outbreak of spots in the STBn jet had recently begun impinging on the GRS, and I suspected that these might have contributed to the high wind speed in 2014 [refs.1 & 9]. However, the HST images from 2009 and 2012 have filled in the record and show that the wind speeds have been similarly fast throughout these years, so the STBn jet spots (which do not appear to have much vorticity in the HST images) did not alter the GRS winds. The results show that the GRS circulation is not affected by supply of vortices from the SEBs jet nor by spots from the STBn jet. This would appear to refute the prevailing hypothesis of how the GRS is powered.

References

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5. HST images taken on 2009 Sep.22: NASA, ESA, M. Wong, I. de Pater, C. Go, P. Marcus, & X. Asay-Davis. (Images kindly provided by Chris Go.)

6. HST images taken on 2012 Sep.20: NASA, ESA, and an international team headed by Dr Glenn Schneider (University of Arizona) and Dr Jay Pasachoff (Williams College and Caltech). (Images kindly provided by Marco Vedovato.)

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9. Rogers JH (2014) Jupiter in 2013/14, Report no. 9: ‘The GRS and adjacent jets: Further analysis of amateur images, 2013/14.’ http://www.britastro.org/jupiter/2013_14report09.htm

10. HST images taken on 2012 April 21: NASA, ESA, A. Simon-Miller, I. de Pater, G. Orton, M. Wong & J. Rogers.

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12. Rogers J & Adamoli G (2015), 'Jupiter in 2005 and 2006: Final report.' http://www.britastro.org/jupiter/2006report13.htm

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Figures & Supplementary Tables are on the following pages

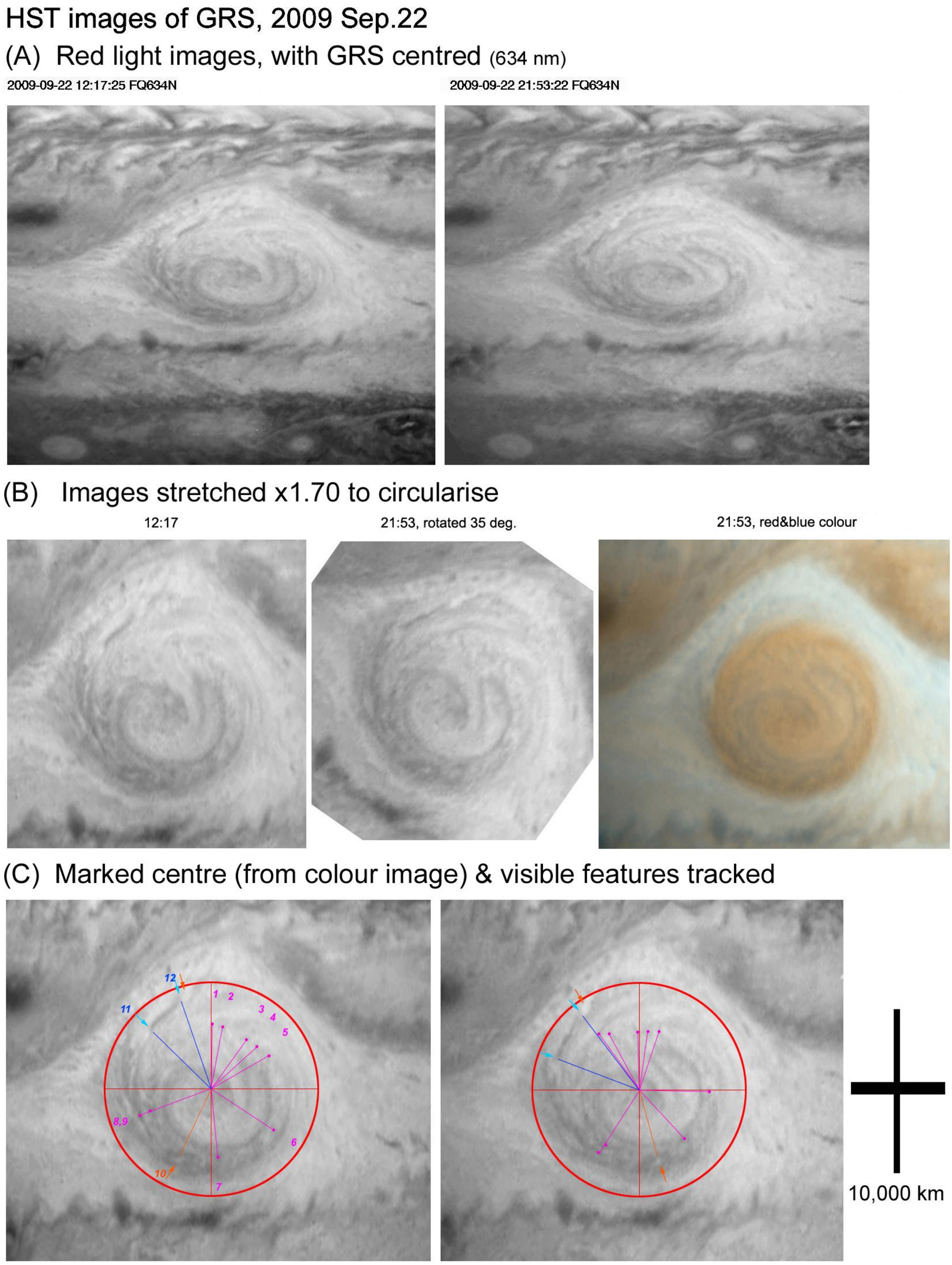

Figure 1. Processing and measuring of HST images of the GRS, 2009 Sep.22.
(A) The red-light images, 12:17 and 21:53 UT, after rotating to put the GRS approx. on the CM.
(B) The same images, stretched x1.70 vertically, with the 21:53 image rotated 35 deg so persistent features can be identified. Right: The 21:53 image with colour image superimposed to show the visible outline of the GRS.
(C) The two stretched images showing points measured.

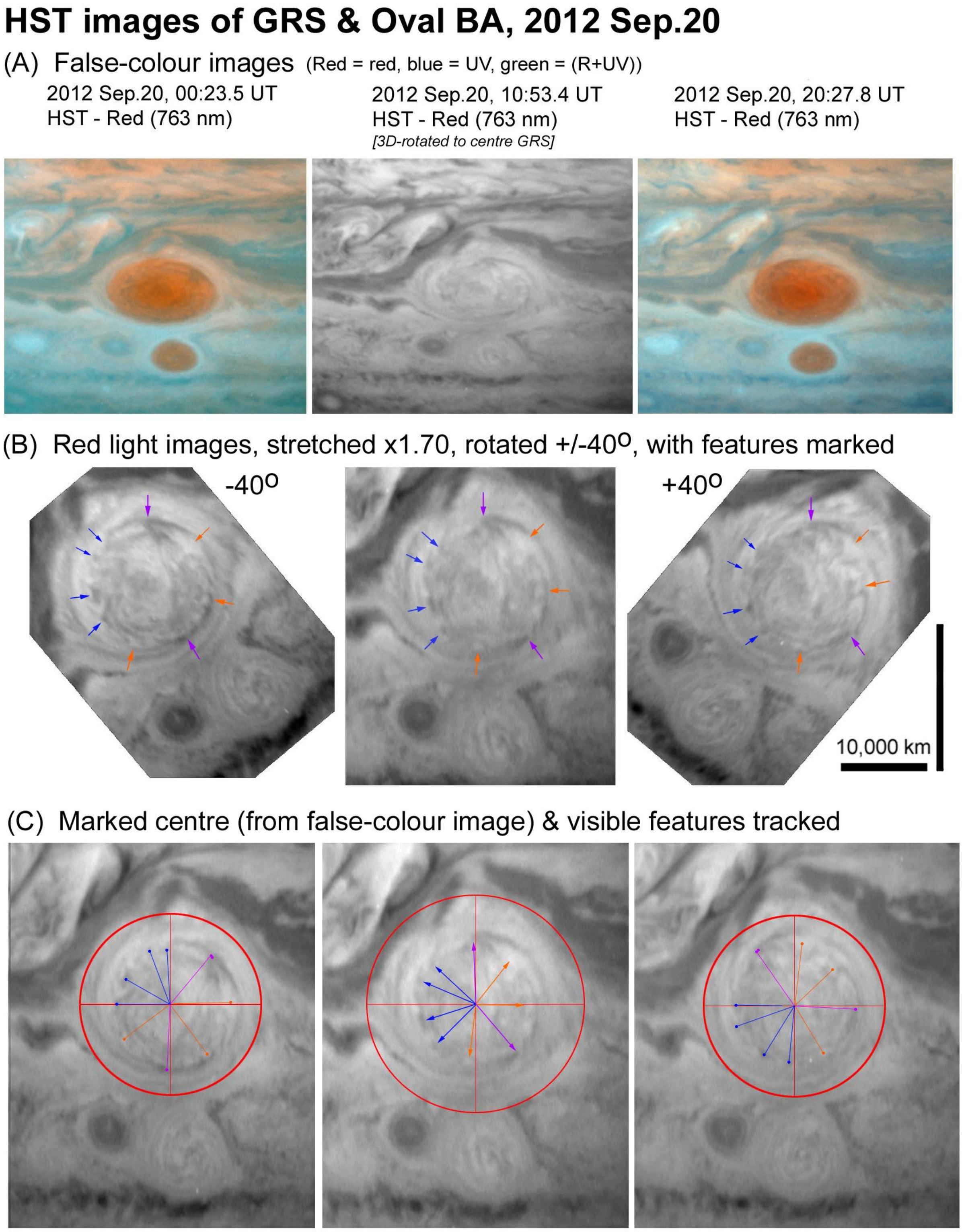

Figure 2. Processing and measuring of HST images of the GRS, 2012 Sep.20.
(A) The three images. The centre image (red light) has been rotated to put the GRS on the CM. The first and third images are coloured by combining the red image with a UV image, to show the outline of the GRS (and oval BA).
(B) The same images, stretched x1.70 vertically, with the first and third images rotated so persistent features can be identified.
(C) The three stretched images showing points measured.

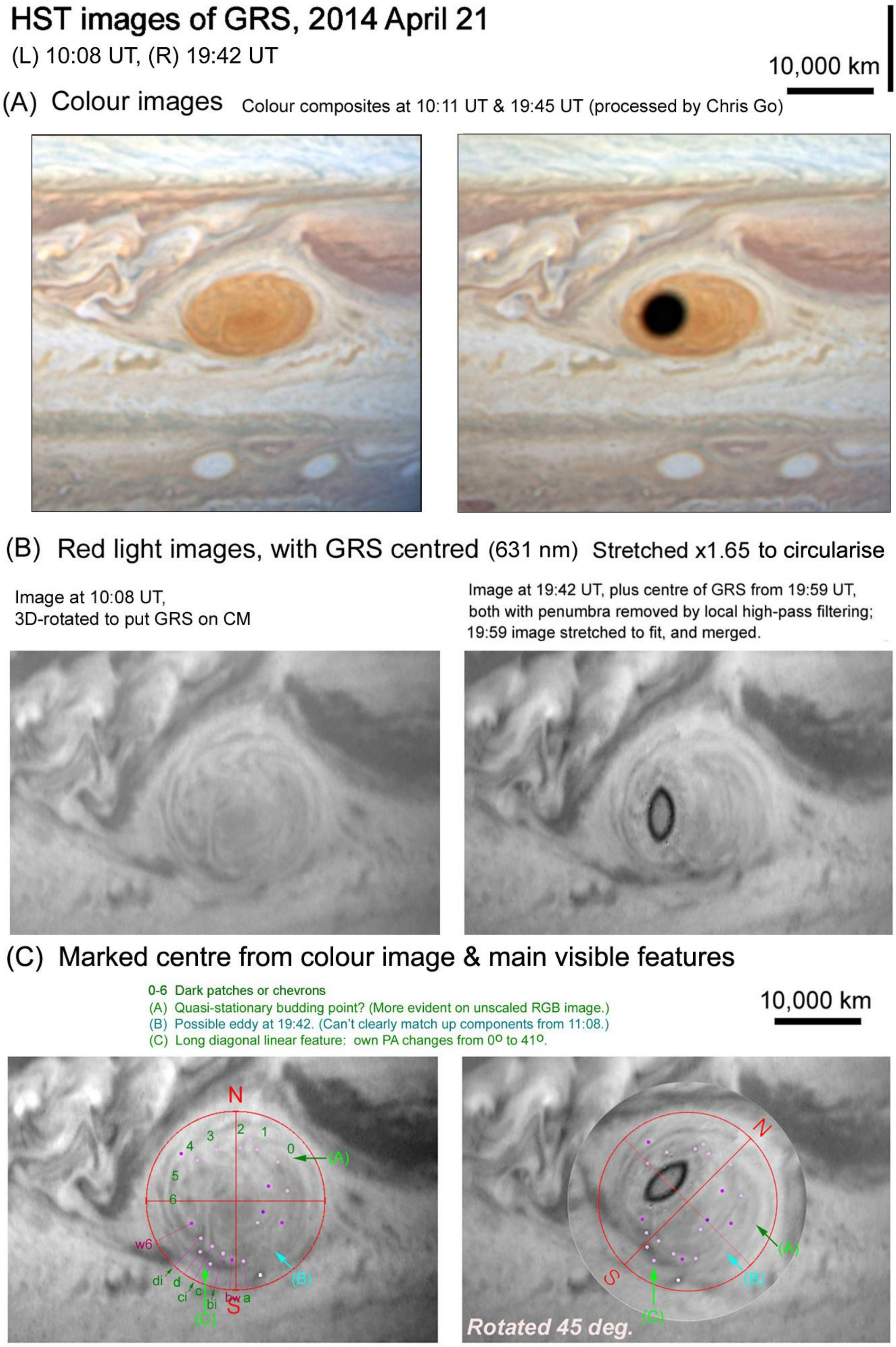

Figure 3. Processing and measuring of HST images of the GRS, 2014 April 21.

(A) Colour images, including the red-light images used in (B), without any reprojection.

(B) The red-light images, 10:08 UT after rotating to put the GRS approx. on the CM; 19:42 UT after processing to remove Ganymede's penumbra as described; both stretched x1.65 vertically.

(C) The two stretched images showing points measured, after rotating the second image 45 deg.

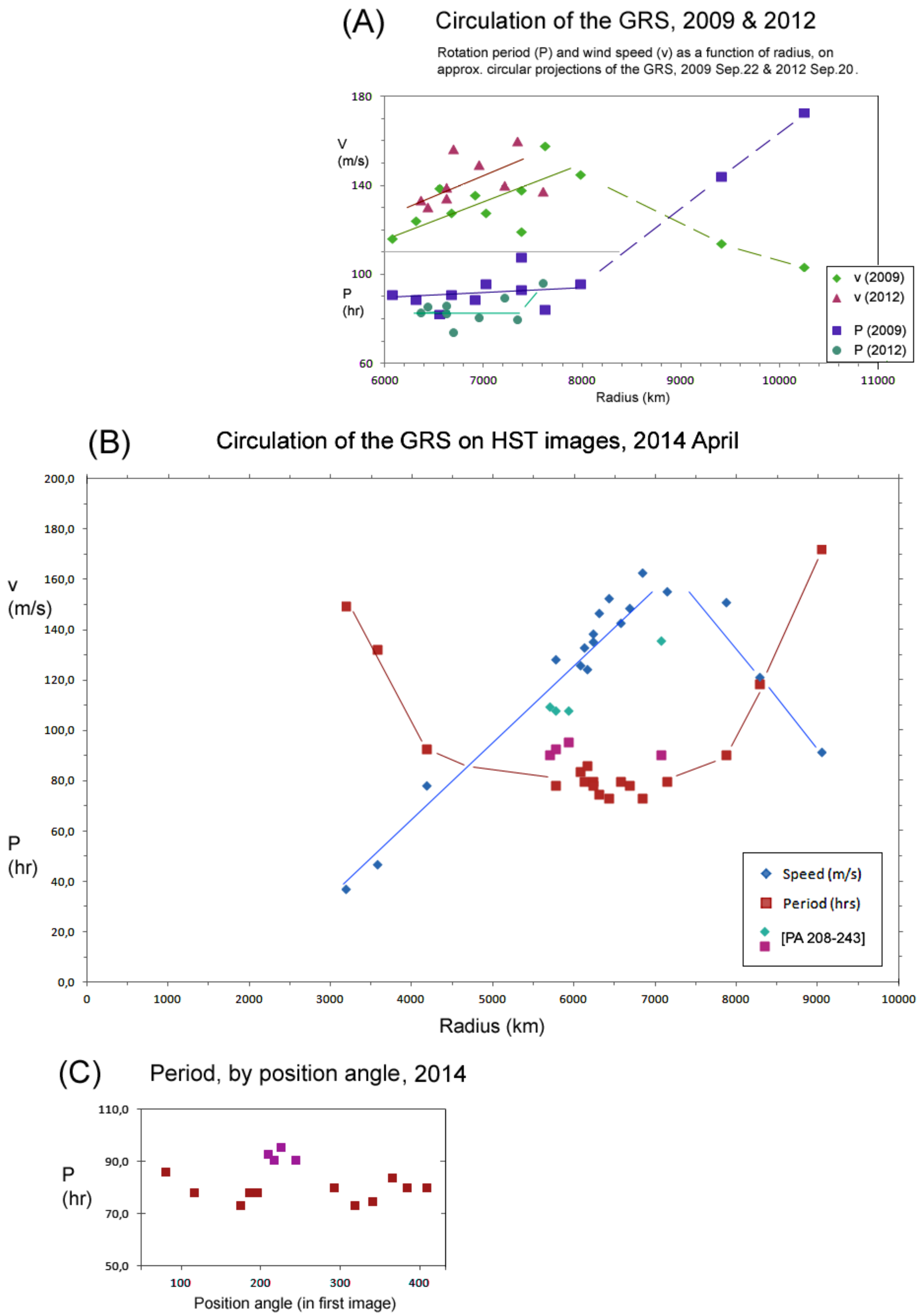

Figure 4. (A,B) Charts of deduced wind speeds (m/s) and rotation period (hours) for the three epochs. (C) Chart of deduced period vs PA in the 2014 data, showing no systematic variation with PA, but a group of unusually slow features (magenta) in one sector.

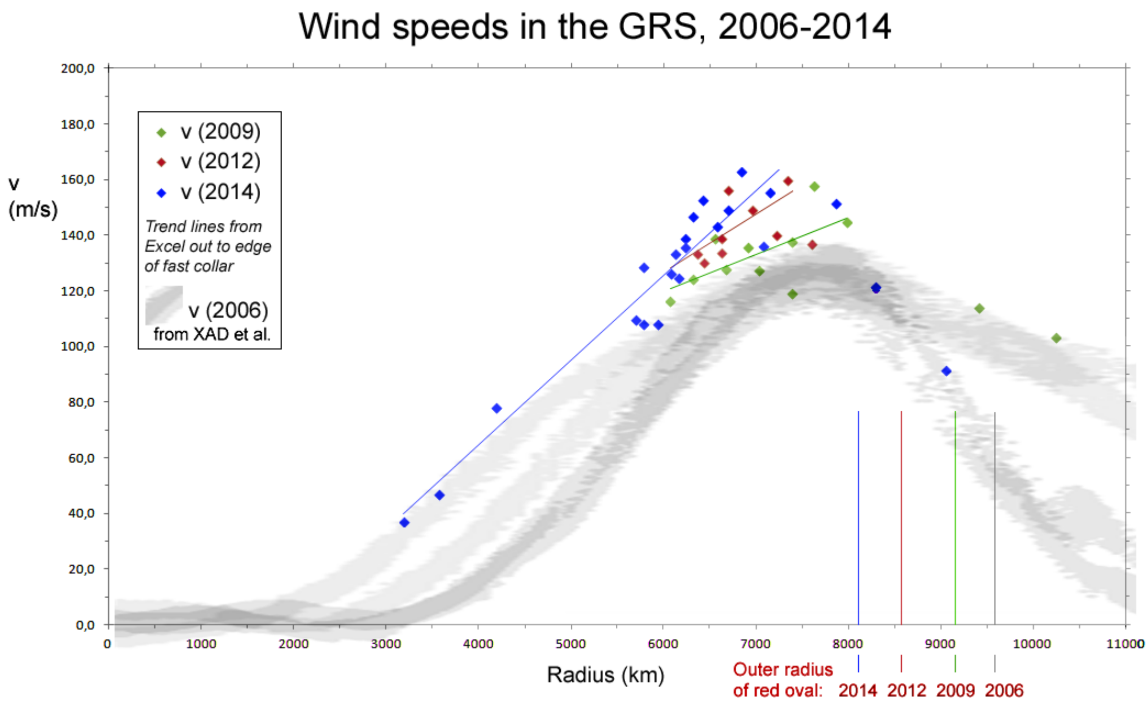

Figure 5. Superimposed charts of wind speeds around the GRS for the 3 epochs, compared with normalised published data from 2006 [ref.4].

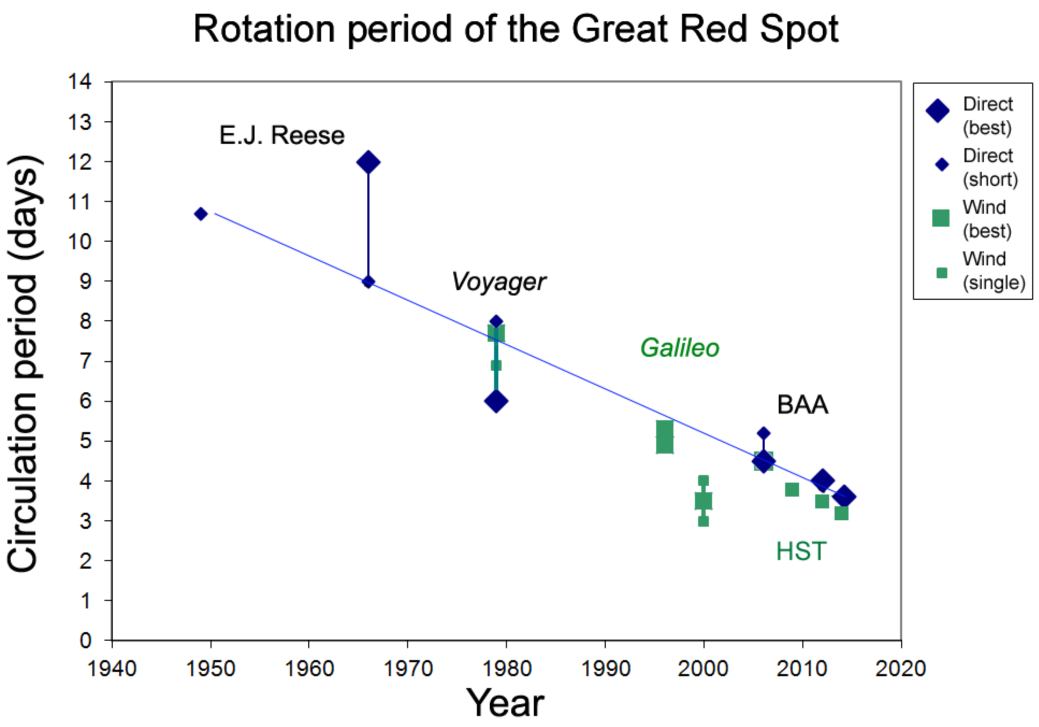

Figure 6. Chart of all measurements of GRS circulation up to 2014, extended from Ref.2. (Data are in Supplementary Table 2, below.) 'Direct' points were measured from features which completed one or more circuits of the GRS. 'Wind' points were deduced from wind speeds measured over ~10-hour intervals. Most of the 'direct' periods fit a linear shrinkage with time. The 'wind' periods are more variable and usually shorter than the 'direct' periods, suggesting that the less stable cloud features reveal faster but more variable winds.

Supplementary Tables

Table 1B. GRS circulation from HST images								
	N	Radius range (km)	Mean P (hrs)	+/-SEM	Mean v (m/s)	+/-SEM	Peak v (m/s)	Mean r (km)
2009 Sep.22								
All features	12	6071-10238	103,0	9,1	129,1	5,0		
Main annulus	10	6071-7976	**91,9**	2,4	133,1	4,2	**151,5**	6988
--inc.3 outer:	3	7381-7976	91,2	3,6	**146,9**	5,8	**149,2**	7659
Peripheral	2	9405-10238	158,4	14,4	108,7	5,3		
2012 Sep.20								
All features	9	6364-7597	84,2	2,5	142,3	3,5		
Main annulus	8	6364-7338	**83,0**	1,9	142,9	3,9	**154,3**	6869
--inc.3 outer:	3	6948-7338	83,7	3,0	**149,8**	5,7	**152,1**	7165
Peripheral	1	7597	96,6		137,3			
2014 April 21								
All features	22	3191-9043	94,3	5,5	122,2	7,1		6234
Main annulus	9	6231-7143	78,8	1,8	146,8	3,1		6611
--inc. peak:	7	6307-7143	78,7	2,3	149,5	3,3		6719,5

The GRS is treated as a projection of circular motion; radius (r) and speed (v) refer to this circular projection, so apply to the major axis (r) and minor axis (v) respectively. SEM, standard error of the mean.

Table 2. Measurements of GRS circulation						
		V(mean) (m/s)	*V(gusts) (m/s)*	*P (days)*	*Major axis (km) [*a]*	*Ref.*
1979 Feb-Mar	Voyager 1	110, 120	140	6-8		[*b]
		135	135			[*b]
1979 Jun-Jul	Voyager 2	110	120			[*b]
1996 Jun	Galileo	135	145	5,0-5,3		[*b]
		115	150			[*d]
2000 May	Galileo	165	190	3,0-3,5	~19800 x (0.7-0.8)	[*e]
		145	180		= 13860-15840	[*d]
		145	170	3,7-4,2	17100	[*f]
2006 April	HST	124 [*c]		4,5	15300	[4]
2006 Apr-Jul	BAA	112		4,5	19800 x 0.7	[2]
2009 Sep	HST	147		3,8	>=16000	This report
2012 Sep	HST	150		3,5	>=14700	This report
2012 Sep	BAA	135		4,0	18560 x 0.8	[3]
2014 Jan	BAA	144		3,6	15800 x 0.9	[1]
2014 April	HST	150		3,2	>=14300	This report

This is an extension of Table 1 in Rogers (2008) [Ref.2].

Notes & Refs:
[*a] Major axis of maximum measured wind speed
[*b] See Ref.2.
[*c] Speeds were -117/+131 m/s in L3, i.e. -121/+127 m/s in GRS rest frame.
[*e] Simon-Miller et al. (2002) [Icarus 158, 249]
[*d] Legarreta & Sanchez-Lavega (2005) [Icarus 174, 178]
[*f] Choi et al. (2007) [Icarus 188, 35]