Long-term report (2017):

Jupiter's high northern latitudes: patterns and dynamics of the N3, N4 and N5 domains

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APPENDIX:
EXCERPTS FROM OUR APPARITION REPORTS
with new JUPOS analysis for unpublished apparitions

1999/2000 *[from our final report in JBAA]*

Report 1999/2000

Other features in far northern currents

In the NNTC, the main features were dark sectors of NNTB (Table 7A), with variable drifts in the range from NNTC to N^{3}TC. These sectors were ~25–50° long, and were quite conspicuous but lasted only a few months, as is typical.

In the N^{3}TC, there were several bright and dark spots (including shorter-lived ones with similar drifts to those listed in Table 7A). The white spots had more stable tracks than the dark spots.

In the N^{4}TC, there was a more regular and stable array of white spots: eight of them were each tracked for 3–7 months, with only small fluctuations in drifts (Table 7B).

Table 7B. Average drift of currents, 1999/2000, northern hemisphere

Current	*Type of spots*	*N*	*DL2: Mean (Range)*	*Lat. range*
NNTC	NNTB segments & NNTZ white ovals	8	–9.3 (0 to –18)	37-41°N
N^{3}TC	Misc. spots	5	–18.3 (–13 to –21.5)	43-45°N
N^{4}TC	White spots	8	+4.7 (0 to +9)	49-53°N§

Notes to Table 7B:
This table gives the mean speed and range of each current, some of which are not itemised individually above.
N, number of spots included (some with multiple drifts).
§ N^{4}TC white spots: Two of these were initially at 52.8 (±0.6) deg.N, but then shifted to 51.4 and 50.9 deg.N. Others were at 50.4 and 49.4 deg.N; average 50.7 deg.N. This corresponds to the cyclonic 'N^{4}TB' domain, which is unexpected, as white spots are more commonly seen at 52-55 deg.N in the anticyclonic 'N^{4}TZ' domain. (All these spots had very similar drift rates throughout.)

2000/01 *[from our final report in JBAA]*

Table 6A. Positions and drifts of spots, 2000/01: Northern hemisphere

No.	*Description*	*Lat.*	*L2(O)*	*DL2*	*Dates*	*DL2(C)*	*L2(1999)*
N^3TC							
1	d.s.	45.3	–	−16	Jul–Aug(Sep)		
2	d.s.	45.8	*	−18	Jul–Sep		
3	d.s.	45.8	*	−20	Aug–Oct		
4	d.s.	45.3	*	−18	Nov–Feb		
5	d.s.	45.3	*	−23	Jan–Mar		
N^4TC							
1	small w.oval	51.2	230	2	Aug–Dec	1?	223
2	small w.oval	51.4	(298)	4	Jul–Oct	5	250
3	small w.oval	50.0	(346)	3	Aug–Nov	1.5	320
NPC							
1	w. oval	54.1 (±0.7)	–	−12	Aug–Sep		
		54.4 (±0.3)	(358)	−47	Oct–Nov		
		53.5 (±0.6)	360	−2	Dec		
		nd	–	−23	Jan		
2	w.oval	59.0	148	+9	Jul–Jan		
3	w.oval	60.8	(205)	+10	Jul–Aug	+13	41
4	w.oval	60.1*	282	+12	(Aug)Oct–Jan		

N^5TC: All longitudes in the range L2 40–110.
NPC no.4: Latitude was +62.3°N in Aug when stationary.

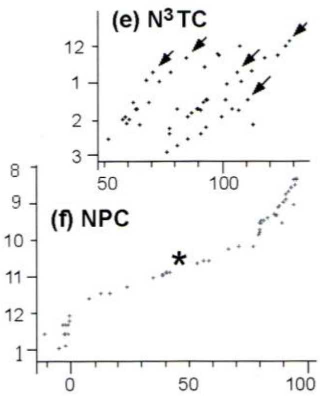

Figure 11. Excerpts from JUPOS charts, showing interesting drifts of spots in longitude, including the previously unobserved jetstreams on NTBn, NNTBn, and N^5TBs. Each chart covers a specified latitude range; on the horizontal axis are longitudes in a system with a specified drift rate per day (a,b) or in System II (c–f); on the vertical axis are months of 2000/01.
(e) N^3TC: 42 to 47°N, L2; small dark spots.
(f) 'NPC': 52 to 60°N, L2; white oval NPC no.1, temporarily moving with the previously unobserved N^5TBs jetstream (*).

[continued on next page]

Table 6B. Average speeds of currents: Northern hemisphere

Current	*Type of spots*	*Sense*	*N*	*DL2: Mean (Range)*	*Latitudes (deg.N)*	*Voyager DL2*	*Voyager Lat.*	*HST DL2*	*HST Lat.*
NIC	Mid-NEB rifts	C	8	−79.9 (−65 to −105)	12 to 13				
NTropC	Dark & bright spots	C/A	19	+0.5 (−6 to +16)	16 to 19	+45	17.6	+25	16.6
(NEBn)	Dark spots/streaks NEB(N)	A	6	−3.5 (−17 to +7)	19 to 20				
NTBs jet	Slight dark projs. NTBs	J	7	−291.8 (−289 to −293.5)	24.9 (av.)	−375	23.8	−322	23.5
NTC-A	Grey projs. & w.ss. NTBn	C	5	+13.1 (+12 to +14)	29				
NTBn jet	Small dark spot NTBn	J	1	+49	31.3	+69	31.6	+27	30.7
NNTBs jet	Tiny dark spots NNTBs	J	19	−76.4 (−72 to −84)	34.6 (av.)	−94	34.5	−106	34.7
NNTBn jet	Small dark spot	J	1	+55	38.6	+31	39.5	+34	38.8
NNTC	Dark segments of NNTB	C	7	~+1 (−14 to +6)	38 to 39				
NNTC	White ovals in NNTZ	A	4	−3.0 (−10 to +9)	40 to 41.5				
N^3TC	Dark spots	C	5	−19.0 (−16 to −23)	45 to 46				
N^4TC	Small white ovals	C!	3	+3.0 (+2 to +4)	50 to 51				
N^5TBs jet	White oval	A/J	1	−47	54.4	−59	56.6	−91	55.1
NPC	White ovals	A/J	3	+10.3 (+9 to +12)	59 to 61				

Notes
This table gives the mean speed and range for each current, some of which are not itemised individually in Table 6A.
Sense: whether the spots were anticyclonic (A), cyclonic (C), or on a jetstream (J). *N:* number of spots included.
DL2: Drift in System II longitude per 30 days. To convert DL2 to DL1, add 228.9°/mth. To convert DL2 to DL3, add 8.0°/mth.
For comparison with our jetstream data, the last four columns give the latitudes and speeds of jets derived from images by *Voyager*[22] and the HST.[24] (The NEBn jet is included for reference although our observations did not detect it this apparition.) The jet speeds have shown real variations, but the latitudes have probably not changed significantly. The HST study derived latitudes that were typically ~1° lower than in the *Voyager* study for these high-latitude jets, and this seems likely to be mainly due to systematic measurement errors. Our latitudes tend to agree better with the HST values.

Higher latitudes

In the *N. N. N. Temp. domain,* the main features were small dark spots at 45–46°N, between L2~ 20–110, prograding with the usual N^3TC (Figure 11e). There were two or three at any one time, lasting up to three months; the more coherent ones are listed in Table 6A.

In the *N. N. N. N. Temp. domain*, the most persistent features were bright spots at 50–51°N, slow-moving, i.e. in the usual N^4TC. Of the best-tracked three (Table 6A), at least two had persisted from the previous apparition. The latitude suggests that these were cyclonic.

One of the most remarkable spots of the apparition was a bright white oval at 54°N with an unprecedented motion (NPC no.1 in Table 6A & 6B; Figure 11f). At first it had DL2~ −12°/mth (variable), then it suddenly accelerated to −47°/mth (Oct–Nov), a speed never before recorded in this latitude. This must be the first ground-based detection of the *N^5TBs jetstream*. The spot's rapid movement is also clearly visible in the *Cassini* movie.[25] Then it suddenly halted (DL2~ −2 throughout Dec); then it accelerated again (DL2~ −23 in Jan). There appears to be a correlation of speed with latitude, in that it travelled fastest when furthest N (54.4°N; Table 6A). So this was an AWO in the N^4TZ domain which wandered in latitude, temporarily entering the N^5TBs prograding jetstream.

Finally, even further north, there were at least three light ovals with speeds of DL2= +11°/mth, at 59–61°N, one of which had persisted from the previous apparition. Bright ovals with similar drift and latitude were also recorded by *Voyager* [pp.83 & 92 of ref.12]. They may represent a retrograding N^5TBn jetstream. The persistence of these ovals is remarkable, and may have been underestimated in the past because we did not plot this latitude range as a whole for previous apparitions.

Discussion: Long-lived anticyclonic ovals

This apparition we have recorded an exceptional number of long-lived spots, mainly anticyclonic ovals, which have persisted through one or more solar conjunctions. These included not only the Great Red Spot and a brown ring in the S. Tropical domain, but also anticyclonic white ovals in almost every other domain: one in the N. Tropical (the fast-moving white spot Z), two in the N. N. Temperate (one being methane-bright), three in the N. N. N. N. Temperate (though the latitude indicates these may be cyclonic), one in the North Polar region, three in the S. Temperate (including the newly merged oval BA), seven in the S. S. Temperate, one in the S. S. S. Temperate, and one in the South Polar region. The latter two high-latitude spots, and the N. N. Temperate ones, apparently persisted between apparitions in spite of showing large and sudden changes in their drift rates.

After our analysis was complete, a survey of long-lived AWOs was published using HST and Pic du Midi images.[13] This survey confirms our tracking of long-lived AWOs at 60°S (their Figures 6 and 10) and 60°N (their Figure 13), and shows details of the dynamics of these polar vortices.

2001/02 *[from our final report in JBAA]*

Report 2001/02

Rogers et al: Jupiter in 2001/2002: Part II *J. Br. Astron. Assoc.* **118**, 4, 2008

Higher latitudes, to North Polar region

According to HST data,[25] prograde jets are at latitudes 42.2°N (N^3TBs), 46.5°N (N^4TBs), 55.1°N (N^5TBs), and 63.5°N (N^6TBs). These can be used to define the domains in the high northern latitudes.

At least five white ovals were tracked in the N^3TC, with a real spread of latitudes from 44 to 46°N (Figure 16c; & Table 8). The two most conspicuous in Figure 4 (N^3TC-1 and 4) were also the fastest moving and the furthest north.

At latitudes 50 to 54°N, many dark and bright spots were almost stationary in L2, representing the typical N^4TC (Figures 16f & 17). However a few of them, especially one at 53.4°N, showed signs of more rapid drift over short intervals, DL2 ~ –20°/mth (Figure 16f), possibly influenced by a prograding AWO at 57.2°N in the next domain to the north (NPC no.1). In these high latitudes the *Cassini* polar movie[35] showed that spots or turbulent regions are quite large compared to the widths of the alternating jets in which they move, and so they jostle one another like people in a crowded railway station. Our chart apparently reveals this jostling, between slow-moving spots (51°N, nominally in the 'N^4TZ' anticyclonic domain) and spots influenced by the prograde N^5TBs jet (55°N) (Figure 16f).

Even further north, two white spots at 60°N with slow positive DL2 had been tracked with similar speed since the previous apparition (Table 8). These may represent a retrograding N^5TBn jetstream.

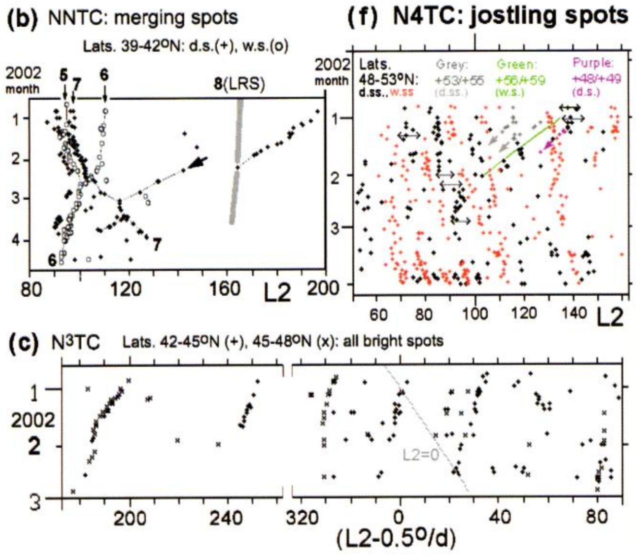

Figure 16. (a–c) Longitude charts in northern latitudes.
(a) NTC-A: latitudes 23–28°N, dark spots; scale moves +0.5°/day in System II. (Diagonal grey line is L2=0 in all charts.)
(b) NNTC: latitudes 39–42°N; scale is System II. Black points, dark spots; open circles, bright spots. This shows the merger of AWOs 5 and 6; ejection of dark spot 7 f. the merged AWO; two rapidly-moving tiny dark spots (indicated by arrows), which terminated at dark spot no. 7 and Little Red Spot no.8 respectively.
(c) N^3TC: Latitudes 42–48°N, bright spots; scale moves –0.5°/day in System II.

Table 8. Longitudes and drifts, 2001/'02. N. Temperate and Polar regions

Current	*Description*	*Lat.*	*Mean DL2*	*N*	*DL2 range*
NTC-C (NTBs jet)	Humps on NTBs	25.1	–293.1	7	–291.5 to –295.5
NTC-B	P. or f. ends of rifts	27.2	–60	7	–60 to –62
	Light sector NTB	27.2	–95	1	—
NTC-A (NTBn jet?)	Small d.ss.	30.6	+28.4	7	+23 to +33
NNTBs jet	Small d.ss.	35.0	–79	2	both accel. from –76 to –82
N^3TBs jet	Small d.ss.	41.5	–28	3	–25 to –30 (irreg.)

Current	*Spot no.*	*Description*	*Lat.*	*L2(O) (Jan.1)*	*DL2*	*Dates*	*Previous L2(O) (2000 Nov.28)*	*Notes*
N^3TC	1	ws	46.0	333	–24	Dec–Jan		
	2	ws	44.0	34	–22	Nov–Mar		
	3	ws	45.5	(84)	–15	Jan–Feb		
	4	ws	46.2	197	–31	Dec–Jan		
	5	ws	43.9	252	–22	Sep–Jan		
	mean	w.ss.	45.1		–22.5	(N=5)		DL2 range –15 to –31
N^4TC	*mean*	(6 spots) (w.ss., d.ss.)	51.1 (range 50.7 to 51.6)	60-150	+1.5	Dec–Feb		DL2 range –3 to +6 (see text)
	1	ws	50.0	(27)	+1	Oct–Dec		
	2	ws	52.2	210	+11	Jan		
	3	ds	53.4	116	+5, –20	Jan		
	mean	w.ss., d.ss.	50.0 to 53.4		+0.6	(N=9)		DL2 range –20 to +11
NPC	1	ws	57.2	132	–25	Jan–Feb		Then halted at L2 = 94
	2	ws	60.1	60	+8	Jan–Feb.	282	
	3	ws	59.5	257	+10	Oct–Mar	148	

2005 & 2006 *[from our final report on-line]:*

N3, N4, N5 domains (North Polar Region)

N3 jet:
In each year, at least one dark spot was tracked at ~42.2ºN with DL2 ~ -40, approaching the peak speed of the N3TBs jet. Another small dark spot in 2006, at 43.4 (±0.5) ºN with DL2 = -63, although sparsely observed, corresponds to the jet peak.

N3 domain (Chart J14):
In both years there were numerous spots, both white and dark, at ~45-46ºN, moving with DL2 ~ -12 to -23, i.e. typical N^3TC. In 2005, similar white spots were also present at ~44ºN. In this domain, according to spacecraft ZWPs, the westward jet at 45ºN does not attain retrograde velocity so we describe it as a velocity minimum (DL2 = -5). Nevertheless, the ZDP **(Fig.41)** is typical in being close to the spacecraft ZWP on either side of 45ºN, but 'blunter' so that the velocity minimum for spots which we detect at 45ºN in each year is DL2 = -10 to -12. But the positions of the spots on either side of the velocity minimum are surprising. In 2005, they were mostly white spots on the southern (cyclonic) side, whereas in 2006, they were mostly dark and white spots on the northern (anticyclonic) side, with the ZDP for white spots ~0.5º N of that for dark spots. Then in 2007 [Ref.1] the ZDPs were almost identical to those for 2006, but with the white and dark spots interchanged! We cannot offer specific explanations. But it may be significant that the N3 domain in spacecraft images is usually packed with FFRs (below the resolution of ground-based images), indicating considerable turbulence, and they sprawl across the velocity minimum, so they may be able to spawn quite a variety of cyclonic and anticyclonic spots, all within the prevailing N^3TC.

N4 domain (Chart J15)
In both years there were slow-moving white spots (with a few dark spots), showing typical N^4TC drift of DL2 ~ 0 (at ~50ºN) to +11 (at ~52ºN, coinciding with the peak of the retrograde jet in the spacecraft ZWP). In this range they had a well-defined cyclonic ZDP **(Fig.42).** In 2005 there were also bright spots at ~53ºN on the anticyclonic side.

In each year, one of the white spots temporarily shifted north (to ~54ºN) and adopted a rapid prograding motion before reverting to its previous latitude and motion. In 2006 **(Chart J15)**, the spot concerned was near L2 ~ 90, at 52ºN on the retrograding jet, with DL2 ~+10 just before and after. In May it suddenly accelerated to DL2 ~-20 for a week or two – apparently dragged behind a large white patch at 57ºN, also moving at DL2 = -20. The images are not sufficient to show details.

N5 domain
In latitudes 55-58ºN, in 2005, there was a short-lived white spot with DL2 ~ -30. In 2006, there was the short-lived white patch at 57ºN with DL2 = -20 just mentioned. These rapid speeds indicate that they were on the flank of the N6 jet. There was also a white spot at 58.5ºN in 2006 April, but otherwise nothing was tracked at >58ºN.

Thus, in both 2005 and 2006 we have detected consistent trends in both high southern and high northern latitudes:
--Variable speeds of long-lived AWOs (sometimes as periodic oscillations, especially in the south);
--detection of spots on almost all prograding jetstreams;
--long-lived sectors of slow-moving dark spots near the retrograde jet (though usually with less extreme speeds, as the ZDPs are 'blunter' than the ZWP on the retrograde side).

2005 longitudes & drifts - N. hemisphere

L2(O) = L2 at opposition on 2005 April 3 unless other date is given.
Dates are for measured track segments, not total life.
N = number of spots measured (number of track segments may be larger).

Current	Description	Name	Lat.	L2(0)	DL2 (deg/30d)	Dates / N
N3 jet	d. spot		42.3	176 (Apr 21)	-37	Apr 21 - May 1
N3TC	(w. spots)		**44.4**	**<--- mean --->**	**-19.6**	(N=6)
			0.80	<--- SD --->	5.2	
	(d. spots)		**45.0**	**<--- mean --->**	**-14.8**	(N=4)
			0.83	<--- SD --->	4.9	
N4 jet?	w. spot		48.2	7 (Mar 31)	-20	Mar 31 - Apr 12
N4TC	(d. spots)		**49.4**	**<--- mean --->**	**1.5**	(N=2)
			0.28	<--- SD --->	3.5	
	(w. spots)		**52.0**	**<--- mean --->**	**6.1**	(N=8)
			0.68	<--- SD --->	5.1	
(N4TC?)	w. spot		54.8	124 (Mar 5)	-19	Mar 5 - 21

2006 longitudes and drifts: N. hemisphere

Current	Description	Spot no.	Lat.	L2(0) (May 4)	DL2 (deg/30d)	Dates	Notes
N3 jet	d. spot	1	43.4	177 (Mar 21)	-63	Mar 21 - Apr 2	At peak of jet (few measures)
	d. spot	2	42.2	181 (May 21)	-40	May 21 - Jun 7	
N3TC	d..ss.	**Mean**	**45.2**		**-16.8**	**(N=7)**	*[Omitted one outlier]*
		SD	0.3		3.5		
	w.ss.	**Mean**	**45.7**		**-17.0**	**(N=3)**	*[Omitted one outlier]*
		SD	0.2		3.9		
N4TC		**Mean**	**51.3**		**4.3**	Dark spots (N=4) & white spots (N=17):	
		SD	0.8		3.4		
(N5TC?)	w. spot	(a)	56.9	89 (May 11)	-20	May 11 - 25	very few measures
	w. spot	(b)	58.5	113 (Mar 30)	-5	Mar 30 - Apr 21	very few measures

2007 *[from our final report on-line]:*

Part 6: N.N. Temperate Region to N. Polar Region

The drift rates of spots **(Table 6 & Fig.33)** generally agree with the spacecraft zonal wind profile **(Fig.1),** except that the spots in N^3TC show a more shallow profile (as in the NTropC). In the N^4TC, as in the high southern latitudes, the spots adhere closely to the spacecraft profile, even when they are stable AWOs or belt segments. In both domains, **Fig.1** indicates that all the spots with DL2 faster than -20 deg/mth are in an anticyclonic zone (N^3TZ or N^4TZ), whereas the latitudes of the slower ones do not clearly indicate their sense of rotation.

N^3-N^4 Temperate Regions

The JUPOS chart shows a widespread, consistent N^3TC with DL2 = -16 **(Fig.33A)**.

A significant disturbance affected latitudes 45-55ºN, longitudes L2 = 220-350, in June, with sudden acceleration of several spots in the N^3TC, and appearance of new spots in the N^3TZ **(Fig.33A)**, and sudden appearance of many dark and bright spots in the adjacent N^4 Temp. region as well **(Fig.33B)**. No such coordinated disturbance, limited in longitude but affecting two adjacent domains, has been observed in such high latitudes before. What was the nature and cause of this disturbance?

In the N^3 Temp. region, the affected white spots and new dark spots were at 45-47ºN (canonical N^3TZ), the accelerated white spots being at the higher latitudes. Inspection of v-hi-res images does not show any obvious cause. The earliest features of the disturbance were at L2 = 270-320, on May 23: acceleration of N^3TC white spot no.6, and appearance of fast-moving dark spot no.10, with another just f. it. These were on Peach's first images taken at Barbados, but the phenomenon was not an artefact of v-hi-res imaging; the white spots were well tracked both before and after their acceleration, and the small dark spots were also recorded by other observers. Could no.10 be a N^4TBs jet-stream spot, initiating a jet-stream outbreak analogous to those at lower latitudes, which generated the disturbance? However, it was not moving with full jet-stream speed. (Peach's images even show an even faster tiny dark spot, catching up with no.10, with estimated DL2 ~ -70 at lat.~47ºN: probably on the true N^4TBs jet.)

From the start of June, other N^3TZ white spots accelerated, and more new (stationary) spots appeared in the N^4 Temp. region at 51-54ºN. Note that accelerations were linked to latitude shifts (Table 6) and there was no change in the zonal wind profile (Fig.1).

While the cause of this disturbance remains obscure, this may be an example where modern observations reveal a phenomenon of these hitherto-obscure high latitudes which does not belong to the categories that we recognise in lower latitudes.

In the N^4 Temp. region, one notable white spot was no.2, which has been tracked since 2006, and was very stable with normal N^4TC drift until it suddenly shifted 2 deg. north and accelerated to DL2 = -30 for just 2 weeks, before reverting. This speed represents partial influence of the next prograde jet ('N^5TBs') at 56ºN, as was also seen for an AWO in 2000/01.

In addition to all these compact spots, the North Polar Region has larger, more irregular features, shown in north polar projection maps by Peach and by Cassini **(Fig.34)**. The NPR (everything N of the NNTZ) has no well-defined belts. It looks like an irregular network of dark lanes, with lighter, vaguely circular patches between them. The Cassini map shows that these light patches are cyclonic folded filamentary regions (FFRs). At lower latitudes FFRs are more localised, but in the NPR they are the largest and most extensive structures, and they are seen even very close to the north pole.

2007: Positions and drift rates: NNTB to NPR

Current/ Spot no.	Description	L2(O)	DL2 (inc. sequences)	Lat.	SD	Dates	Notes
N3TC							
2	DS	(65)	-18	45.6	0.52	Feb-Apr.	[There is no no.1]
3	WS	150	-15	45.4	0.6	Apr.-Aug.	
4	DS	156	-16.5	45.6	0.93	Feb-July	
5	WS	(256)	-15	45.5	0.54	Apr-May	Var. drift before and after (Feb-Aug.)
6	WS	(275)	-12	44.9	0.42	Apr-May	faster before and after (Feb-Aug.)
7	WS	320	-17	45.3	0.57	Feb-June	faster after (see below)
8	WS	(178)	-16	44.4	0.58	July-Aug.	
Mean (spots 2-8):			-15.6	45.2	0.4		(N=7)
Disturbed sector, June-August:							
5b	WS		-30 (var.)	46.6	0.66	June-Aug.	Suddenly accelerated
6b	WS		-25	45.3	0.49	May 23-June 12	Suddenly accelerated
			-28 to -15 (v)	45.5	0.60	June-Aug.	
9	WS		-16	44.4	0.76	June-Aug.	New
10	DS		-33	46.0	0.31	May 23-June 9	New
			-15	45.7	0.63	June-Aug.	
7b	WS		-28 (var.)	46.0	0.72	June-Aug.	
11	P. end dk. streak		-20	46.0	0.41	June-Aug.	
12	WS		-13	45.1	0.55	July-Aug.	
N4TC							
1	DS	68	-1	49.8	0.5	May-July	
2	WS	155	+6.6	52.3	0.7	Feb-July	Tracked since 2006; v. stable until
			-30	54.3	0.67	July 17-31	sudden switch in lat. & drift
			(+3.5)	53.8	0.3	Aug.3-Sep.3	
3	WS	(248)	-19	54.5	0.8	Apr.24-May 14	Alongside N3TC no.3
Disturbed sector, June-August:							
4	3 WSs	220-265	+6	51.6	0.8	June-Sep.	
	& one of these:	228	-1	50.3	0.6	July-Aug.	
5	5 DSs	240-360	mean +6	52.9	0.7	June-Aug.	
			range +3 to +9				
6	3 DSs	230-270	mean +6	50.6	0.9	July-Aug.	
7	1 DS	--	-19	54.2	0.9	July25-Aug.18	

2010/11
Report no.9:

NPR: The filamentary regions resolved

From spacecraft imaging we know that sprawling turbulent cyclonic areas (‘Folded Filamentary Regions’: FFRs) are a permanent, widespread feature of the NPR. V-hi-res images in mid-Sep. by Peach, Wesley, and Combs managed to resolve them into innumerable chaotic spots, and to show rapid changes in them. These have been displayed by Vedovato as polar projections **(Fig. 23)**, which allow the chaotic motion of the FFRs to be tracked, insofar as their rapid chaotic changes allow. The latitudes of these regions, and of adjacent white ovals, fit perfectly between the mean latitudes of prograde jets as revealed by spacecraft (47.4, 55.8, 63.8ºN), confirming that the images detect cyclonic FFRs from 47-55ºN and 56-62ºN, and AWOs at 45, 54 & 62ºN.

Fig.23. The extensive chaotic activity in the NPR. North polar projections from images by Damian Peach and Brian Combs, Sep.13-20, in which the chaotic cyclonic folded filamentary regions (FFRs) of the NPR are resolved and tracked. The first image is repeated with FFRs roughly outlined in light blue, AWOs arrowed in pink, and lobes of the N. Polar Hood outlined in mauve; and a zenographic latitude scale. The observed structures fit precisely into the domains as expected from the latitudes of the prograde jets. White ovals are all anticyclonic (AWOs), just S of the jets. FFRs are cyclonic but fill virtually all of the high-latitude domains.

[**Addendum (see Fig.23 & JUPOS chart)**: A long-lived N5 AWO at ~62N retrpgrades to L2 = 310 then instantaneously reverses and moves N to prograde rapidly. It is S of the main band of N5 FFRs at 56-62N. There are also superb images showing it on most dates from Sep.1-13 (not compiled), but they don’t show any reason for its sudden acceleration. It is a small AWO with dark rim, but its surroundings are not reliably resolved.]

New JUPOS analysis:

2010/11: Mean drift rates

Current		*DL2*	*SD*	*Lat.*	*SD*	*N*	*Notes*
N3 jet	D.ss.	-37, -51		(42-43ºN)		2	First detection
N3TC	W.ss. & d.ss.	-17.3	4.1	n.d.		10	Normal range
		(range: -13 to -24)					
	W.ss. & d.ss.*	-28.9	5.5	n.d.		8	Fast group*
		(range: -24 to -40.4)					

*Various high-latitude white and dark spots in 2010 Aug-Nov. These showed widespread acceleration, but were interspersed with white spots with normal speed.

N4TC	W.ss. & d.ss.	+5.0	0.5	n.d.		5	Main spots
	W.ss. & d.ss.	+5.1	2.4	49.7 to 53.3ºN		13	All spots (slow tracks)

‘Main spots’ are the best-tracked spots (3 white, 2 dark), for consistency with earlier years.
‘All spots’ are from full JUPOS analysis by G.A. (9 white, 4 dark), all with similar N4TC drifts for at least part of their tracks, spread over wide latitude range.
Four of these white spots also had fast segments in their tracks, long or short, the fastest being:

	W.s.	-22		53.4		1	
	W.s.	-24		53.9		1	
	W.s.	-40		53.8		1	

Two white spots probably merged in 2010 Dec.

N5TC	(w1-w4)	+14.5	3.9	60.6	0.6	4(8 tracks)	
	(w5)	Var. prograding drift, possibly starting as w1 --> DL2 ~ -50, then mod. fast inc. DL2 = -10.5 (62.5ºN) for 1 month.					
N6 jet	(w6)	-47.6		64.5		1	

2011/12 *[from our final report on-line]:*

North Polar Region: N3, N4, N5 and N6 domains

North of 43ºN (the N3 jet), there was a generally dark and mottled texture with no prominent belts or spots, but hi-res images revealed innumerable spots and more complex structures, as has previously been seen in spacecraft images. **Fig.35** shows five north polar projection maps in 2011 Nov-Dec., which dramatically show the chaotic landscape of the region. Many small dark spots and several bright spots were tracked in these four domains, all having drifts close to the known ZWP, as shown in **charts JUPOS-N3, N4, & N5-N6**, and **Fig.7**. North of the N3 domain, the only features lasting more than 2 months were a few white spots, presumed to be AWOs.

In the N3 domain, many dark spots and several bright spots were tracked. About half the spots had speeds around DL2 = -15.4 (±2.3) deg/mth, at lat. 45.4 (±0.3)ºN (N=13), i.e. the classical N^3TC; these included a row of about 6 anticyclonic rings or dark spots from L2 ~ 210-300 in Sep. (visible on Fig.30). The other spots had more scattered speeds, from DL2 = -3 to -40, mostly on the anticyclonic side. One of these was an AWO which had crossed the N4 prograde jet (see below).

In the N4 domain, there were short-lived dark spots, mostly on the cyclonic side, whereas bright spots were mostly on the anticyclonic side (Fig.7). All had drifts typical of the N^4TC, averaging DL2 = +5 deg/mth. The only persistent and fairly conspicuous features were two AWOs. They, and some smaller white spots, tended to maintain fixed speeds for a while but then undergo sudden, sometimes extreme changes in speed, as we have noted in other apparitions. The larger of them (N4-WS-a, or 'W7') was methane-bright (Fig.5), and so was the smaller (N4-WS-b, or 'W3') during its notable transition on Nov.26 & 29.

An AWO moved from the N4 to the N3 domain!
The smaller AWO (N4-WS-b, or W3) underwent a remarkable transition in late Nov., when Chris Go noticed a pair of white spots here that looked as though they were merging. In fact, what occurred was much more surprising: this AWO shifted from the N4 domain to the N3 domain, splitting and then recombining as it did so! **(Figs.32&33)** Its initial speed and latitude (DL2 = +8 deg/mth, 51.4ºN) placed it on the retrograde jet, then it moved rapidly south in late Nov., crossing the prograde (N4) jet at 47ºN. As it did so, on Nov.26, it split into two white spots which orbited round each other clockwise (anticyclonically) by ~140º in 13 d, until Dec.9-10, when they merged again to form a single AWO prograding at 46ºN in the N3 domain.

What impelled this AWO to undergo such a dramatic shift is not clear. One may suspect the adjacent turbulent FFRs (labelled FFR-a and –b in Fig.32), which were in close contact with it; in particular, the large FFR-b emitted a streamer north of the AWO which could have driven the AWO to the south. The spot(s) adhered closely to the ZWP throughout the transition (Fig.33), splitting just as it crossed the prograde N4 jet, presumably due to the anticyclonic shear on its S flank, and then recombining within the anticyclonic N3 domain.

This is the first instance, to our knowledge, of a spot crossing across a prograde jet. The closest parallel reported, in Cassini images, was when a FFR in the N4 domain generated a small AWO in the adjacent N3 domain [ref.18 Fig.2b]. But such an event may not be exceptional at these high latitudes, which have only recently been resolvable by amateur images. We have seen signs of interactions between high-latitude domains here in other years, and spacecraft have shown large FFRs that spread across the jets. In the Cassini north polar movie [ref.19], the whole region was seen to consist of numerous spots and large turbulent FFRs constantly jostling one another, and the prograde N4 and N5 jets were seen as statistical averages but not as smoothly channelled flows.

In the N5 domain, there were several persistent white spots, again with notable interactions and variations in drift and latitude, though adhering to the ZWP. Two pairs underwent interactions.

W1 and W2 appeared to show a complex interaction on the chart (JUPOS N5-N6), but the images (Fig.34) show that despite close contact on Aug.24, they simply passed each other, producing temporary oscillation in the drift rate of each. W1 started with DL2 = -43, at 63.0ºN in the anticyclonic zone, and after the conjunction it underwent two cycles of oscillation to speeds as slow as +2.5, at 62.3ºN, before resuming steady drift of DL2 = -48, at 63.4ºN. W2 started with DL2 = +11, at 60.3ºN on the retrograde jet, then underwent one oscillation after the conjunction, before resuming steady drift of DL2 = +16, at 60.5ºN. The figure shows that just before the conjunction, another white oval appeared just S of the two spots, at ~56ºN, which was probably cyclonic.

W3 (a tiny AWO; DL2 = +14, 61.6ºN) and W4 (a light cyclonic patch; DL2 = -29, 57.0ºN) converged steadily until they were in contact (N-S) on Oct.6, then they disappeared; the interaction may have destroyed both.

The behaviour of these spots may well be typical of these latitudes, although rarely visualised; similar drifts and phenomena were recorded in the Cassini imagery.

Summary of measurements, 2011-12: N. hemisphere

(JUPOS data - GA's analysis)

This Table lists the major individual spots (black type) and means and standard deviations for currents (red type).
L2(O) = L2 at opposition on 2011 Oct.29
Dates are those for track measurement; the spots may have been followed for longer with variable or imprecise drift rate.
N = no. of measurements, for single spots; no. of spots (in brackets, no. of track segments), for means.

Region / spot	Dates	L2(0)	DL2 (deg/mth)	Lat.	N	Notes
N3 domain (N3TC)		**Mean**	**-15,4**	**45,4**	13	Mean limited to 'core group' of dark spots with DL2
Dark spots		SD	2,3	0,27		from -10 to -20, lat.45 to 46 N (about half the spots
						in N3 domain) (N3TC).
W2	Nov 25 - Jan 4	(125)	-30,6	46,3	25	AWO translocated from N4 domain (W3)
N4 domain (N4TC)						
Dark spots		**Mean**	**4,6**	**50,8**	18	Means of all spots at 49-54 N (N4TC)
		SD	5,2	1,1		
White spots		**Mean**	**5,1**	**52,0**	8 (12)	
		SD	5,4	1,2		
including AWOs:						(See fuller table in report text.)
WS-a (W7)	Jun 28 - Nov 24	339	8,1	51,8	174	
WS-b (W3)	Sep 23 - Nov 15	98	8,0	51,4	61	Then translocated to N3 domain (W2)
N5 domain		Mean	13,5	60,4	11	Mean of all spots, 59-62 N.
		SD	7,3	0,8		(4 white, 7 dark)
						(See text for individual spots.)
N6 domain						
White spot	Sep 24 - Oct 23	67,6	-91,4	67,3	28	
	Oct 26 - Dec 20	76,4	-46,6	66,5	32	

Finally, one more white spot was recorded with remarkably fast drift and high latitude, in the N6 domain, on the flank of the **N7 jet** (see chart, JUPOS_N5-N6, & Fig.35). It had DL2 = -91 deg/mth at 67.3ºN! (Although the drift rate sounds extreme, this equates to a quite modest speed, +16.4 m/s, due to the high latitude.) After October, it decelerated to -47 deg/mth at 66.5ºN.

The polar projection maps in **Fig.35** give a panorama of the region, which has no well-defined belts, and is packed with chaotic structures. In addition to the white ovals described above, the maps show many large FFRs; their turbulence is partially resolved in some maps, whereas in others they just appear as irregular grey patches. The most well-defined FFRs are outlined on the maps and can be seen to persist over several weeks, though with variable shapes. Most notably, there is a broad band of persistent light patches (possible FFRs) at 70-75ºN, further north than anything we have ever tracked. There are plenty of other features which cannot be confirmed from one map to the next, partly because these features are at the limit of ground-based resolution, but possibly also because they are indeed rapidly variable. Similar NPR maps are in our reports for 2007 [ref.11] and 2010 [ref.17]. The Cassini polar map [reproduced in ref.11] and movie [ref.19] showed a very similar picture at much higher resolution, with many light patches even at 70-80ºN, and revealed how extensive and turbulent these FFRs and other structures were in the north polar region.

2012/13

New JUPOS analysis by G.A.:

2012/13: Mean drift rates

Current		*DL2*	*SD*	*Lat.*	*SD*	*N*	*Notes*
N3TC	W.ss. & d.ss.	-23.4	3.7	n.d.		11	
		(range: -19.3 to -29.7)					
N4TC	W.ss. & d.ss.	+5.7	3.3	51.7	1.2	5	All spots (slow tracks)
			(range 50.1 to 54.1ºN)				

The numerous slow-moving (N4TC) white and dark spots, common in previous years, are largely absent! Of the 4 best-tracked WOs, only one (w1) is consistently in the N4TC; another (w3) is so until 2013 Jan. when it accelerates to fast speed. Others (w2, w4) have fast speeds, with fluctuations, for most of the apparition, up to -12.4 and -31. Also one exceptionally fast w.s.:

N5 jet	(w6).	-56		54.7		1	
N5TC	(w2,w4,w6)	+15.8	3.0	60.2	0.8	3	Slow w.ss.

(w1) Oscillating between +5 and -45, along ZDP from 61.6 to 63.3ºN (2012 July—2013 March); irregular period 1.7—3.4 months. w1 and w2 passed each other in 2012 Sep., uneventfully, but then: (w2-w3) Possibly also a single w.s. with DL2 varying from +13 to -57, along same ZDP, from 60.5 to 63.5ºN. Merged with w1 on Dec.15 [see new compilation] without change of speed.
After this, w1 was the only tracked w.s., probably = w1 in 2013/14.

N6 jet	(w5)	-56		65.4		1	

2013/14

New JUPOS analysis by G.A.:

2013/14: Mean drift rates

Current		*DL2*	*SD*	*Lat.*	*SD*	*N*	*Notes*
N3 jet	D.s.	-78		(42-43ºN)		1	Fastest detection ever
N3TC	W.ss. & d.ss.	-20.5	3.7	n.d.		9	All spots except fast pair
		(range: -13 to -24)					
	D.ss.	-38, -42		n.d.		2	Fast pair
N4TC	W.ss.	+3.1	1.0	52.1	1.0	4(5)	Slow tracks (DL2 positive)
			(lat. range: 50.7 to 53.0ºN)				

As in 2012/13, the most prominent spots (w1, w2) were mostly fast-moving, with fluctuations; both were high-latitude AWOs. Fast track segments ranged from -22.2 (53.9ºN) to -43.8 (54.6ºN). There were several slow-moving w.ss., of which w3 & w3A (which merged) were the most prominent. There were only a few short tracks for dark spots.

N5TC	(w1)	+11.6		60.5	0.4	1	

The only conspicuous spot. Mean drift, Sep.--> April. Slight oscillations but always slow.

2014/15 *[from our final report on-line]:*

North Polar Region (N3, N4, N5 domains)

North of the NNTZ, the NPR showed no conspicuous features except for a very dark brown bar at L2 ~60 in the N4 domain (d1), but there were many white ovals (all likely to be anticyclonic [AWOs]), and innumerable small dark spots and mottlings. This region has no well-defined belts, and is packed with chaotic structures. All this is typical, and is shown in several v-hi-res image sets (Figs.15-17) and polar projection maps (Fig.18).
Similar polar projection maps were published in our final reports for 2007, 2010, and 2011/12 (Fig.35 therein). The Cassini polar map movie [Ref.21] dramatically showed the chaotic motions in this domain, within which the standard jets and currents emerge as average motions. [Because the NPR is no longer tilted towards us, the maps do not consistently show the v-hi-lat patches that were recorded in 2011/12. Hints of belt structure at >70ºN are probably artefacts of processing, as discussed for the SPR.]

The drifts were also typical, being segregated by latitude into the canonical N^3TC [mean DL2 = -18.1 (±4.4) deg/mth, at 45ºN] and N^4TC [mean DL2 = +5.4 (±3.6) deg/mth, at 50-51ºN], with faster-moving AWOs further north at ~54ºN and ~62.5ºN.

N3 domain:
There were many small rings (AWOs) moving with the N^3TC. They are visible in various figures, including Figs.17 & 18.

N4 domain [JUPOS chart N4]:
This domain was well populated, though not so crowded as in other apparitions. There have been obvious differences in spot population between apparitions. In 2011/12, white and dark spots were uniformly distributed along the domain. In 2006, features were mostly white spots, in the cyclonic domain. In 2014-15, dark spots were in the cyclonic domain, white ones in the anticyclonic latitudes.
As in the past, spots adhered closely to the Cassini ZWP; the ZDP (Fig.11) showed much less southward shift than for the NNTC and N^3TC. Many short-lived features had slow drifts typical of the N^4TC. The most conspicuous feature was a very dark bar at L2 = 60, 51ºN (Jan.-March). The only long-lived spot in the N^4TC was w7 at 51ºN (see below).
There were also three long-lived AWOs further north at 53-54ºN, with much faster, more variable drifts. They were bright white with dark rims. The first two were tracked throughout the apparition, and possibly since 2013. The changes in drifts were sometimes gradual but sometimes abrupt, taking place within no more than a few days.

a) N4-AWO-a: The most conspicuous AWO at 54ºN. It oscillated irregularly between fast and slow speeds, from -4 to -39 deg/mth, as is typical for these hi-lat AWOs. It passed w7 in early February. In spite of their difference in latitude, they interacted anyway, as w7 showed a notable northward migration from 51.0 (±0.3) to 52.5 (±0.6) ºN, starting around the time of their conjunction, though without change of speed; it survived only one month thereafter. The conjunction is shown in **Fig.16**. (**Spot w7** was a tiny white oval throughout, even when in contact with AWO-a; only its latitude changed. After the conjunction, w7 was well shown in Fig.13; it looked like AWO-a and –b, though smaller, up to March 6. These latitudes imply that w7 was wafted by the passing AWO from the retrograde jet into the anticyclonic domain; the images suggest that it became a well-formed AWO, so it is not clear why it did not survive.)
b) N4-AWO-b: Tracked from Oct. to April. It is well shown in Fig.13. Like AWO-a, it oscillated continuously between fast and slower drift rates; after a fast run in Nov-Dec., it underwent 3 cycles with period 25-30 days from Jan. to March, before disappearing.
c) N4-AWO-c: Tracked during a 3-week slow-moving phase (-2.7 deg/mth, 53.3ºN), though it had much faster, variable drifts before and after. **Fig.17** shows how a tiny w.s. began as a filament of a FFR on the S edge of AWO-c, and then persisted as a tiny w.s. for a month.

We have not identified specific causes for the sudden changes in speed of these AWOs, but interactions with the seldom-resolved turbulent features of the region are possible. For instance, the sudden drift changes of AWO-c in Feb.&Mar. occurred while a large FFR lay on its southern edge **(Fig.17)**.

N5 domain:

Two AWOs were observed with rapid prograding drifts, at 62.5(±0.1)°N. One of them was well documented, for about two months, accelerating slightly. They lay perfectly on the Cassini ZWP.

Spot	*Tme interval*	*L2(0)*	*DL2*	*Lat.*	*N; n*	
N3 domain (N3TC)						
W. spots		Mean	-20,6	45,2	7	
		SD	4,0	0,25		
D. spots		Mean	-16,4	44,7	10	
		SD	*3,9*	*0,57*		
N4 domain:						
W. & d.spots (N4TC):		Mean	5,4	50,6	6	
		SD	*3,6*	*0,7*		
AWOs :						
AWO-a	Oct.18-Dec.6		-6,7	nd		
	Dec.6-Feb.21	298	-30,8	53,9	34	oscillating
	Mar.10-Apr.21		-4,7	53,4	31	
	May 12-Jun.12		-17,1	53,7	10	oscillating
AWO-b	Oct.22-Nov.10		5,7	nd		Ill-defined
	Dec.5-Jan10		-40,0	nd		
	Jan.10-Mar.31	46	-22,3	53,9	37	oscillating
	Apr.1-May 22		8,0	nd		
AWO-c	Nov.9-Feb.21		-14,4	nd		
	Feb.26-Mar.16	225	0,0	53,3	9	
	Mar.16-May 12		-41,4	nd		ill-defined
N5 domain:						
	Feb 8 - Mar 7	161	-24,8	62,6	12	

2015/16 *[from our final report on-line]:*

North Polar Region and N3, N4, N5 domains

Anticyclonic white ovals (AWOs) were tracked in each of these high-latitude domains.

N5 domain:
Four white spots were tracked here, ranging up to 62.5°N; all had drifts very near the Cassini ZWP.

N4 domain:
Many white spots (often with dark rims) and small dark spots were tracked in this domain.
Two of the white spots (W1 and W2) were quite large ovals, and may have persisted from the previous apparition, although due to their unpredictable speed changes we cannot identify them with certainty. Most spots were on the broad retrograde peak (11 dark and bright tracks, including W2 and briefly W1: mean DL2 = +6.4 (±2.0), lat.50.4 to 53.2 °N). From mid-Nov. to mid-Jan., W2 (at 52°N) was very close to a white oval in the N5 domain (at 59°N), both moving with DL2 = +9 to +10. However W1 and W2 also spent long intervals at higher latitude with large prograde drift (mean DL2 = -26.1 (±1.1), lat. 54.1 (±0.2) °N), implying that they were AWOs. W1 and W2 are indicated in **Figs.8-10**.

N3 domain:
There were many well-defined tracks of both dark and white spots; two of the white spots lasted throughout the apparition. They all fell on a well-defined ZDP; most spots were on the anticyclonic side. As last year, the plot suggests a possible shift of the ZWP retrograde peak by about 0.5° southward.

Spot	*Time interval*	*L2(0)*	*DL2*	*SD*	*Lat.*	*SD*	*N; n*
N5 domain							
White spots							
W1	Oct 26 – Jan 13	162	10,2		59,3		18
W2	Apr 7 –22	135	7,2		61,2		18
W3	Apr 12 – May 5		-12,7		62,5		8
W4	Apr 5-18	232	6,4		61,3		9
N4 domain							
White spots							
	Dec 29 – Feb 9		*-25,0*		*53,9*		*13*
W1	Mar 5 – 14	291	5,9		53,2		7
	Apr 11 – Jun 17		*-27,0*		*54,2*		*33*
	Oct 30 – Feb 19		9,1		51,9		26
W2	Feb 26 – Mar 29	149	-2,5		53,3		27
	Apr 3 – May 6		*-26,6*		*54,2*		*16*
Mean of fast tracks (W1, W2):			***-26,2***	*1,06*	***54,1***	*0,17*	*3*
N4TC = Mean of slow tracks (all spots):			**6,4**	2,0	**51,8**	0,96	11
N3 domain							
N3TC = Mean of all w. & d. spots:			**-18,7**	4,53	**45,1**	0,32	26
(except two faster ones)					**43,9**	0,15	3

N2 domain [excerpt]:

Folded filamentary regions (FFRs): These turbulent cyclonic regions have been recorded in the N2 domain in spacecraft images, but only in the last few years have they been routinely resolvable in amateur images – in 2015/16, especially by Go, Olivarez, and Peach. So we can now record the timecourse of FFRs and begin to interpret how they interact with other features. This is important, as it now seems likely that they are largely responsible for changes in most other features of the domain, viz. changes in the drift rate of anticyclonic ovals, production of retrograding dark spots, and production of prograding spots on the N2 jet [see below]. Our interpretations are well supported by the beautiful v-hi-res maps from Hubble on 2016 Feb.9 (**Fig.9;** Ref.5).....

....It thus appears that both LRS-1 and WS-6 were held up at the f. edge of the respective FFRs for several months, then broke free and prograded along their northern sides. This raises the possibility that the mysterious irregular drifts of anticyclonic ovals, in this and other high-latitude domains, may be influenced by FFRs which could not hitherto be resolved. Possibly the natural speed of the ovals is prograding, but they can be held up temporarily by FFRs (which belong to the N.N. Temperate Current, i.e. near-stationary in L2), as well as by retrograding dark spots [refs.3 & 6].

3. Rogers J & G. Adamoli G (2016) 'Jupiter in 2014/15: Final numerical report.' http://www.britastro.org/jupiter/2014_15report12.htm
5. Simon AA, Wong MH & Orton GS, NASA & ESA: OPAL project: https://archive.stsci.edu/prepds/opal/ . [Colour maps kindly provided by Dr Amy Simon.]
6. Rogers J & Adamoli G (2015), 'Jupiter in 2011/12: Final report up to 2012 Feb.' http://www.britastro.org/jupiter/2011report09.htm