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Jupiter's high-latitude storms: A Little Red Spot tracked through a jovian year

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ON-LINE SUPPLEMENT

This 'Online Supplement', available on the BAA web site, includes:

Figs. S1-S10.
Tables 1-5 [some may also be printed].
Appendix 1: The LRS in 1993.
Appendix 2: The LRSs in 1994.

FIGURES:

[Notes:]
The versions provided (GIFs and JPEGs) may need to be re-made as TIFs from the original files for printing quality. Captions above the line on figures are to be deleted.
Figures S1 to S10 (along with Tables 1-5 and Appendices 1 and 2) will be published in the On-line Supplement. Figures S1 to S6 supplement Figures 01 to 06 respectively.

We could also post on-line GIF files of Figs.2, S2, & S9A (the big JUPOS charts), as PDFs will not be adequate.

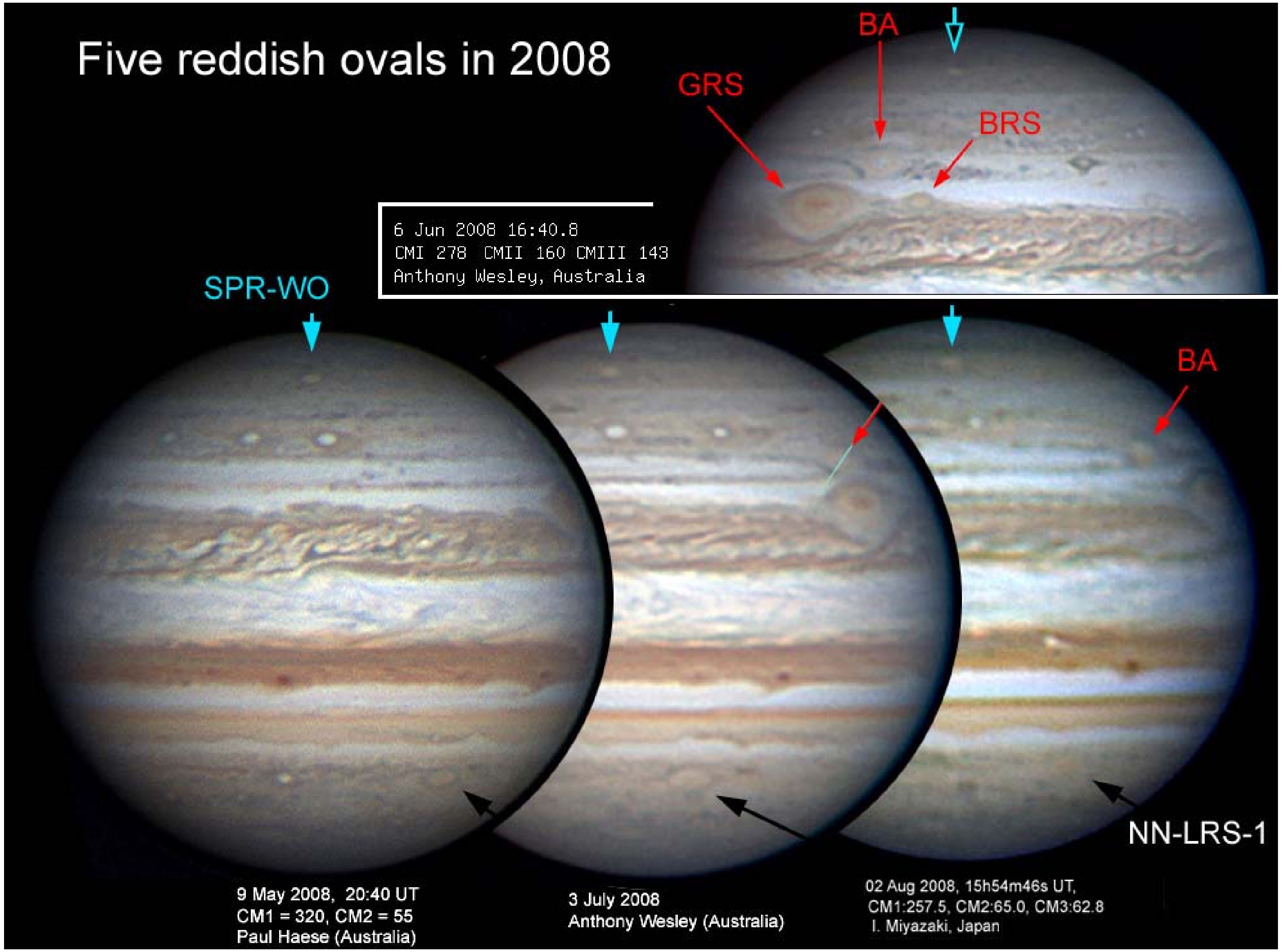


Fig.S1. Images in 2008 showing 4 Red Ovals & the SPR-WO. Three images show the long-lived NN-LRS-1 and SPR-WO, with the GRS and oval BA on the f. limb. *Top right:* The GRS, Oval BA, the short-lived STropZ LRS, and a second, smaller SPR white oval. Images by P. Haese, A. Wesley, and I. Miyazaki.

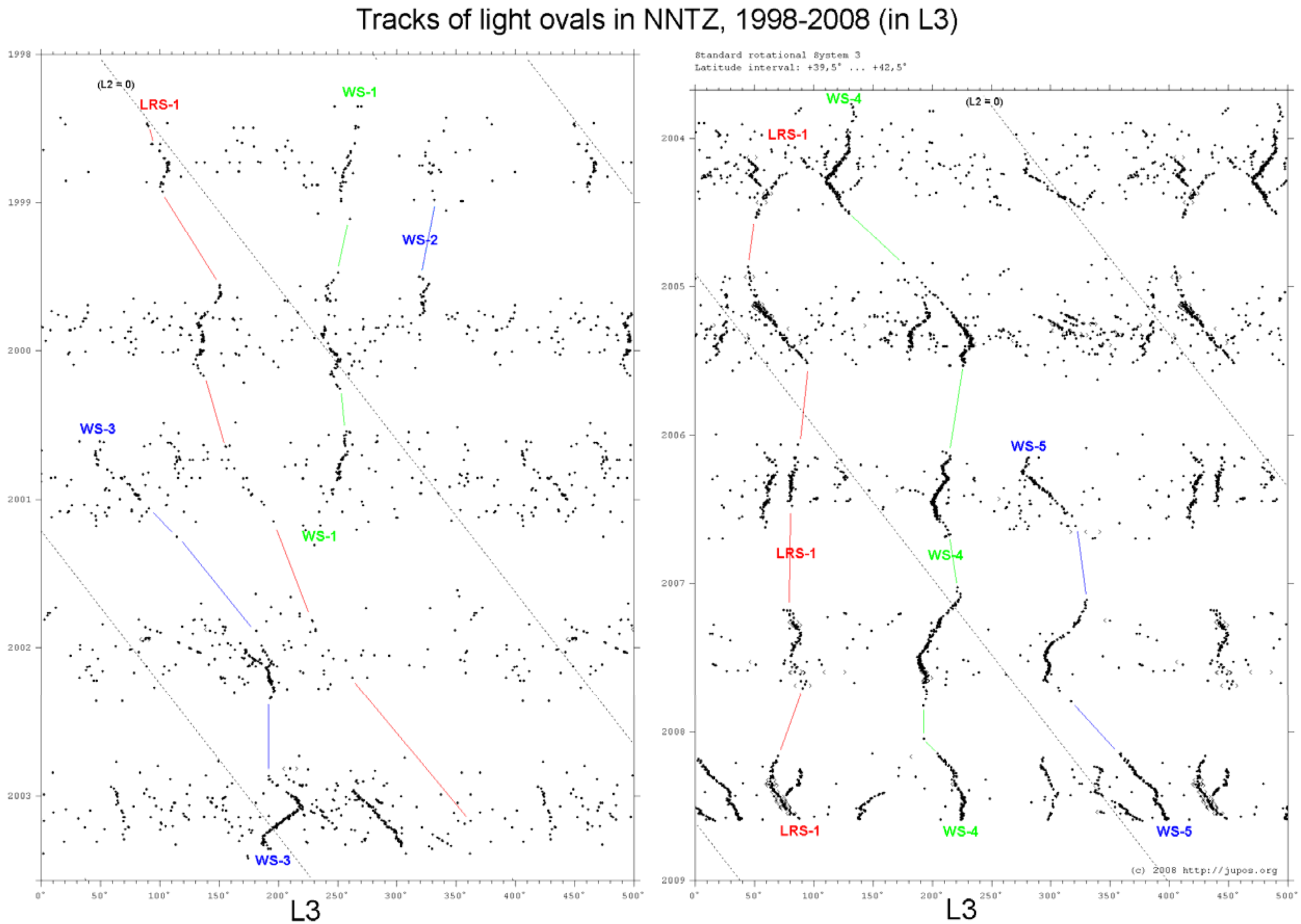


Fig. S2. Chart of longitude (L3) vs. time, JUPOS data as in Fig.2 but plotted in System 3. The dashed line marks L2 = 0.

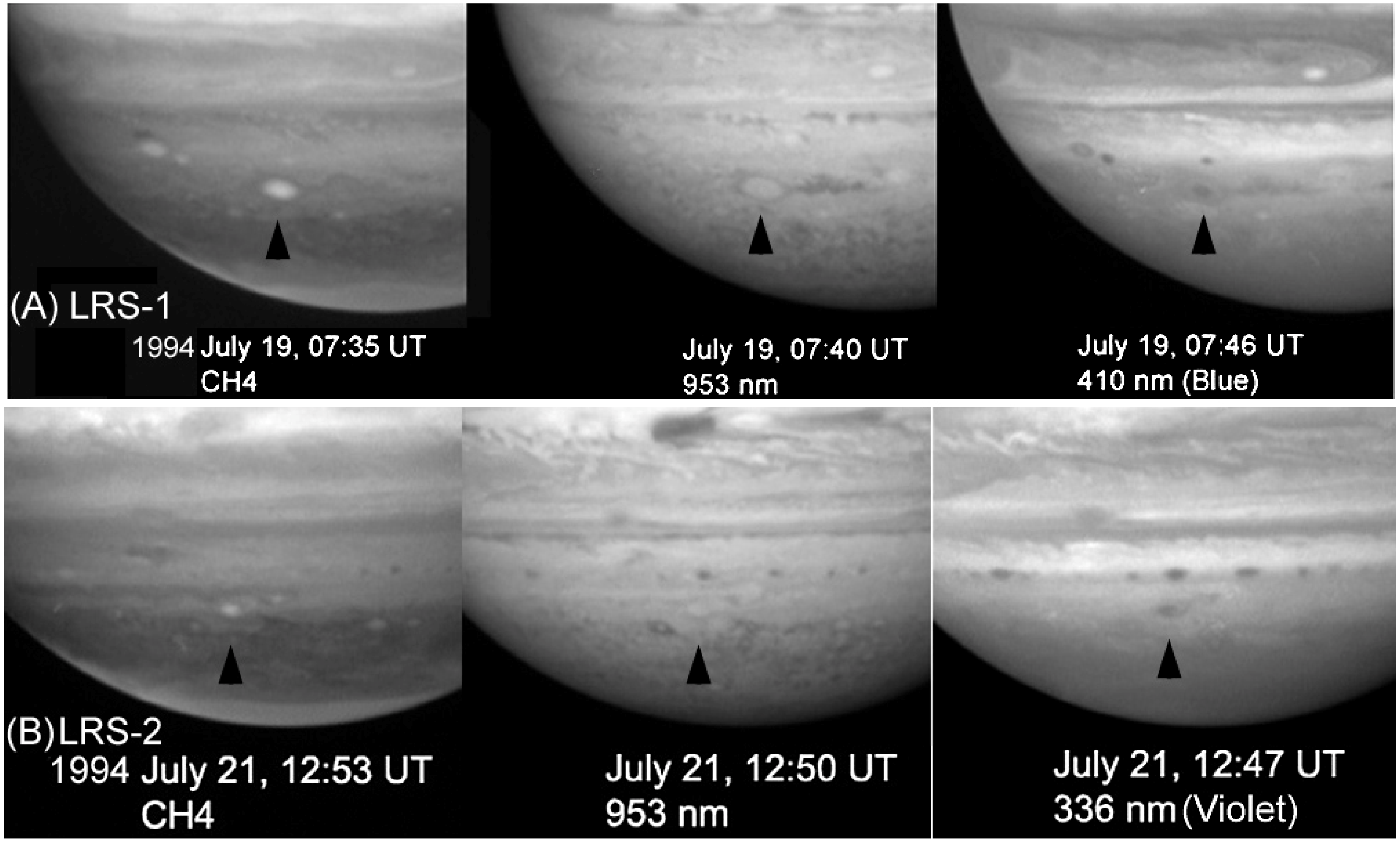


Fig.S3. LRS-1 and LRS-2 in 1994 July 19 & 21, from HST (WFPC-2). Both are bright in methane and infrared wavebands, and dark in blue or violet. LRS-2 is smaller than LRS-1. To upper left of LRS-1 is another LRS prograding in the NTZ. *[Credits: Ref.34]*

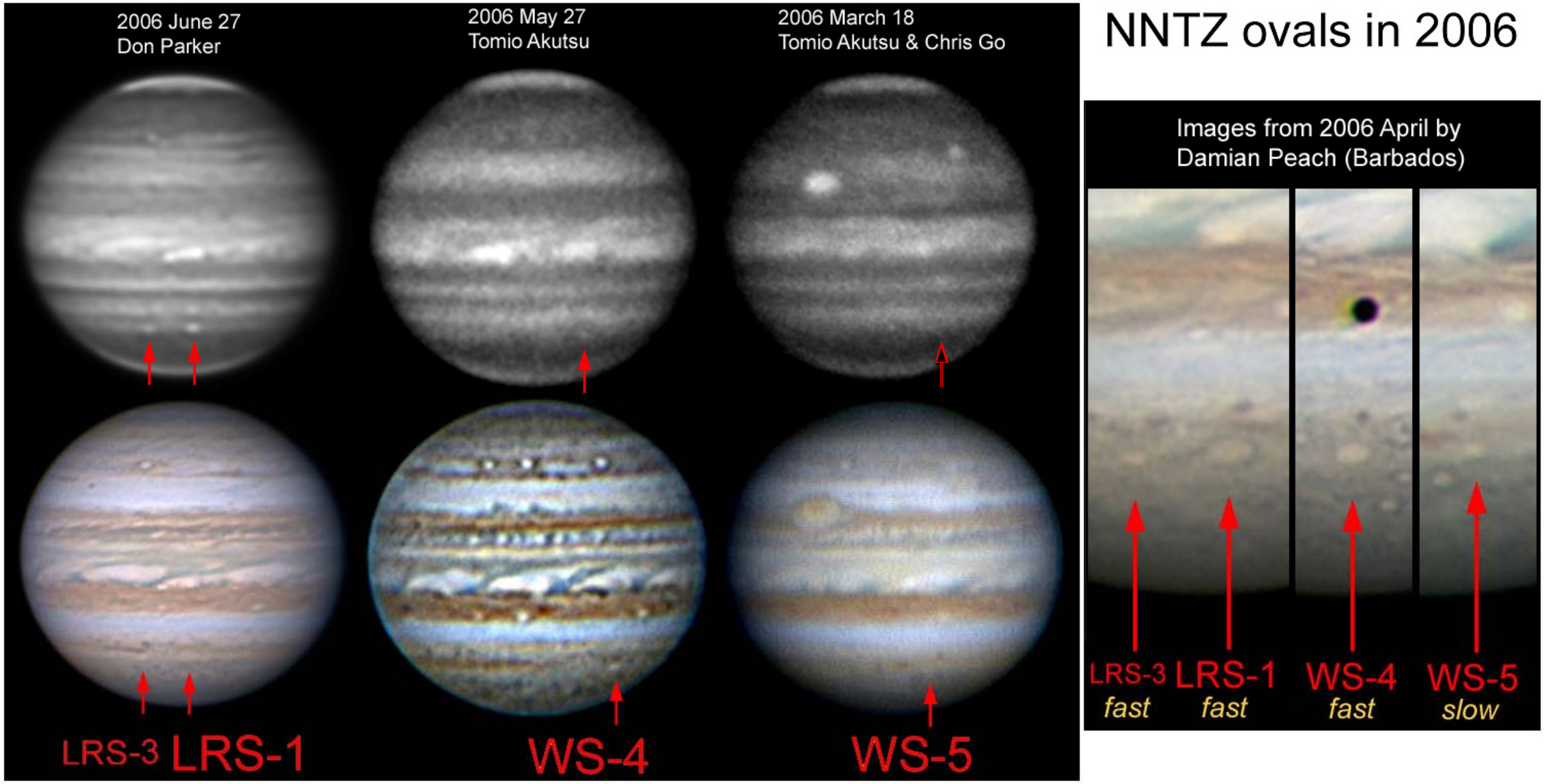


Fig.S4. LRS-1, WS-4, WS-5, and a short-lived small LRS p. LRS-1, in 2006. Methane-band and colour images by Tomio Akutsu, Don Parker and Damian Peach. LRS-1 was very weakly reddish. Note that the small LRS p. it (here labelled LRS-3) was clearly methane-bright, while WS-5, of the same size, was not (also see Fig.4).

Fig.S5. Histograms of drift rates, as in Fig.5, for each class of ovals separately.

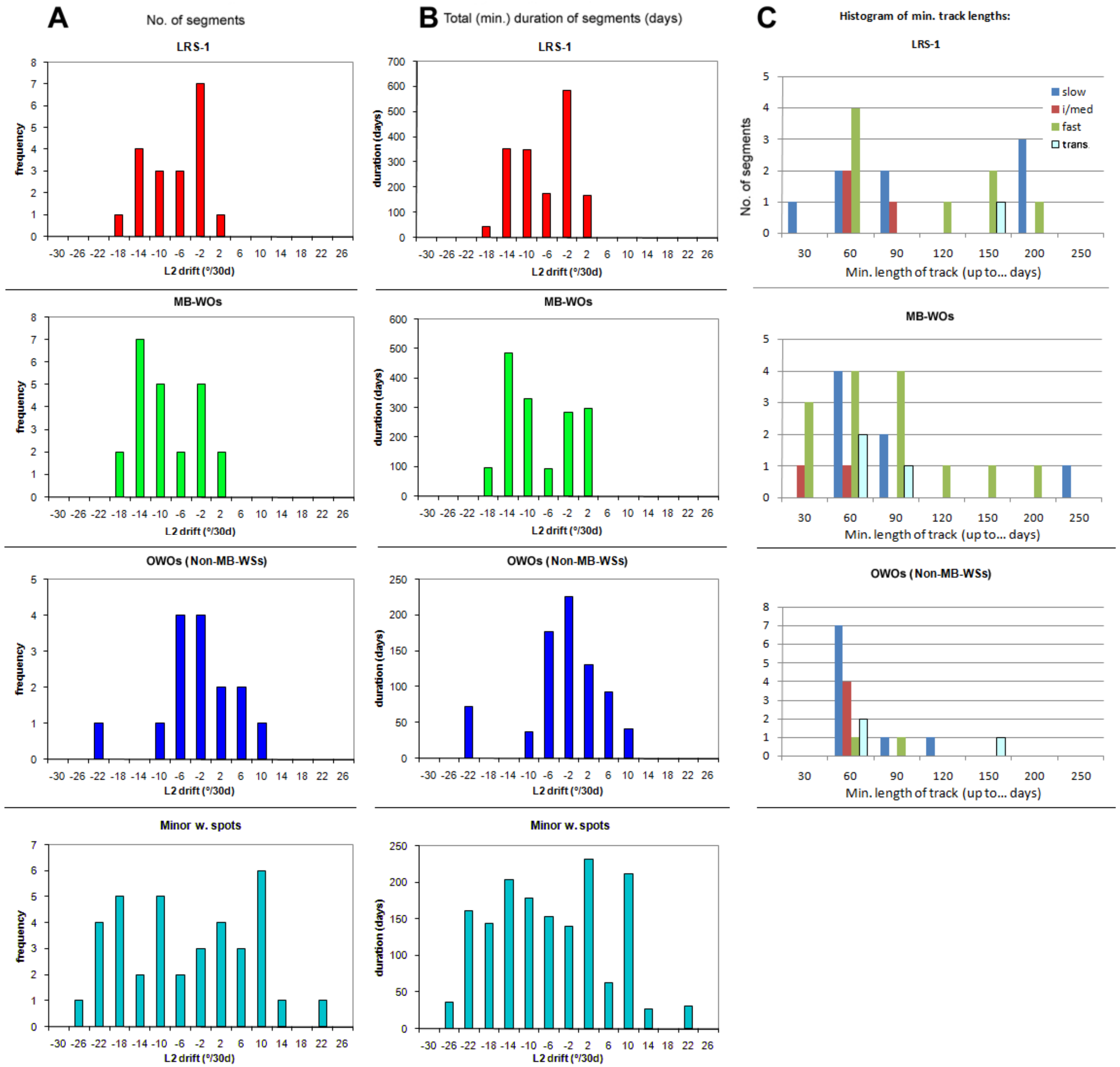


Fig.S6. Charts of drift rate vs. latitude, as in Fig.6, with minor white spots added.
(A) 1998-2006. The 4 classes of spots follow parallel regression lines. The point for LRS-1 in 2001/02 (red open symbol) has been excluded. If it is included (Fig.6), the regression line has a gradient of -10.903.
(B) 2007-2008. The 4 classes of spots still show correlation between speed and latitude, although over too small a range in these years to plot meaningful regression lines. However, the points for LRS-1 and the MB-WO now lie ~0.4 deg further north than in Fig.6, for unknown reasons. All white spots now fall close to the Cassini line.

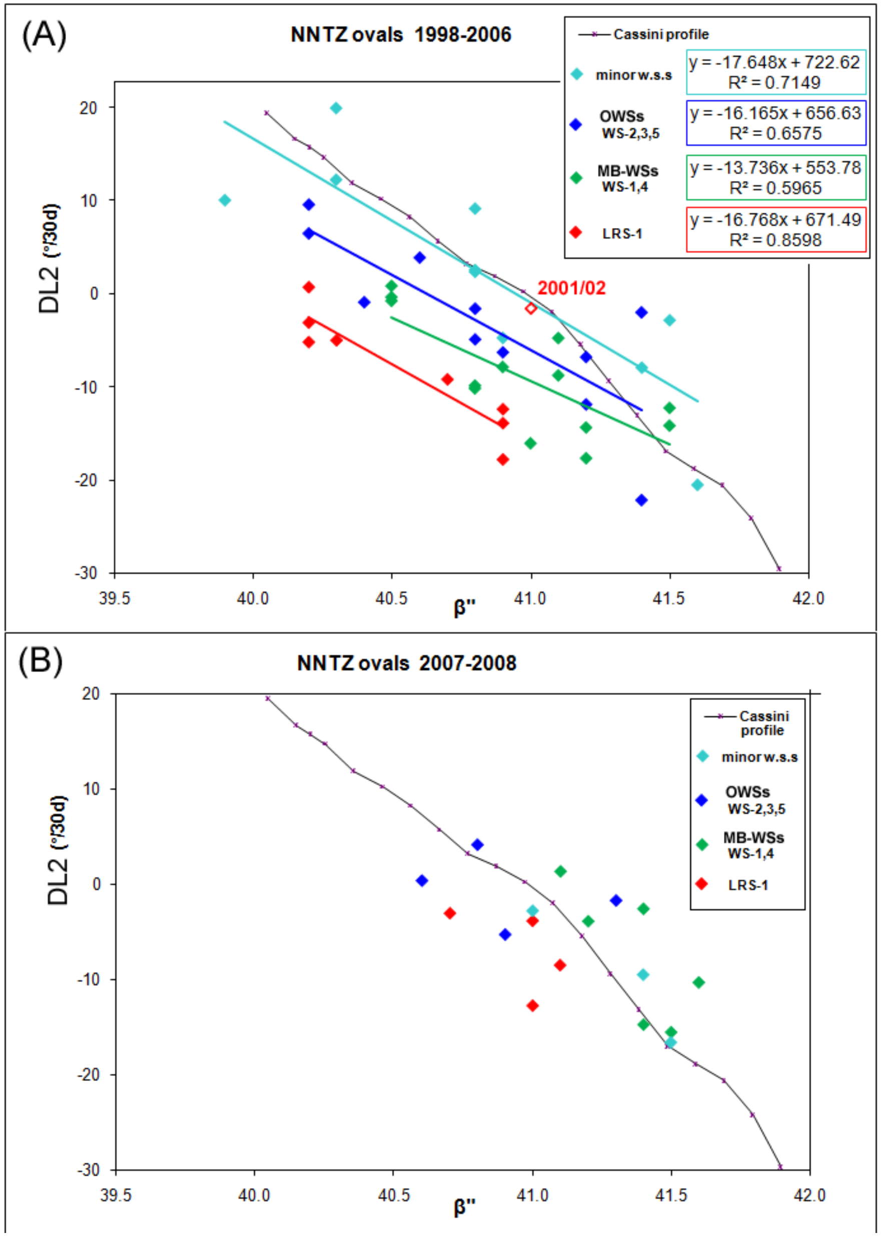
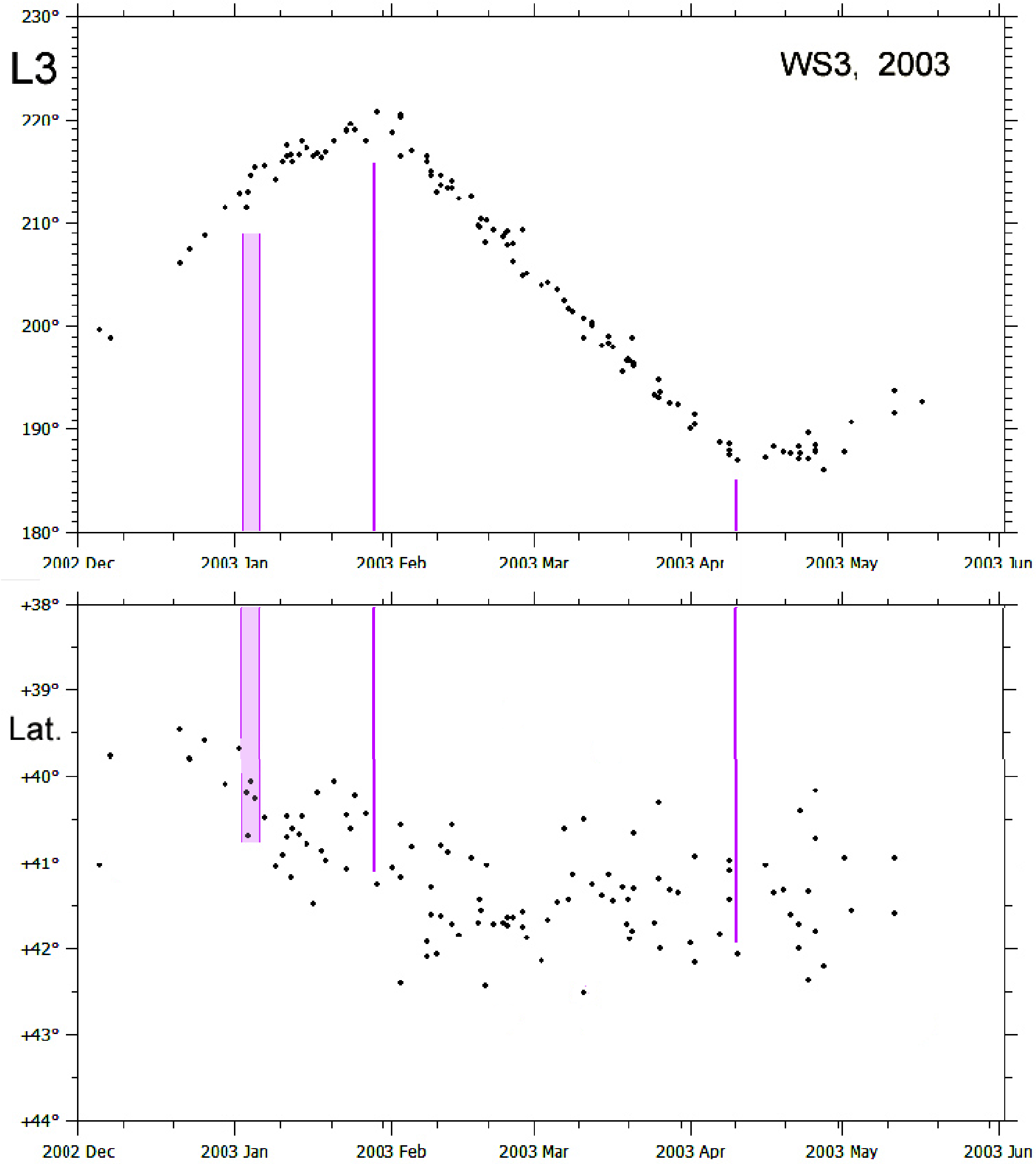


Fig.S7. WS-3 in 2003: Charts of longitude (L3) and latitude (β”) vs time. Shifts in latitude and speed are simultaneous within the precision of the measurements. The last segment contains the last observations of this oval, which may be why the latitude is further north than in the second segment.



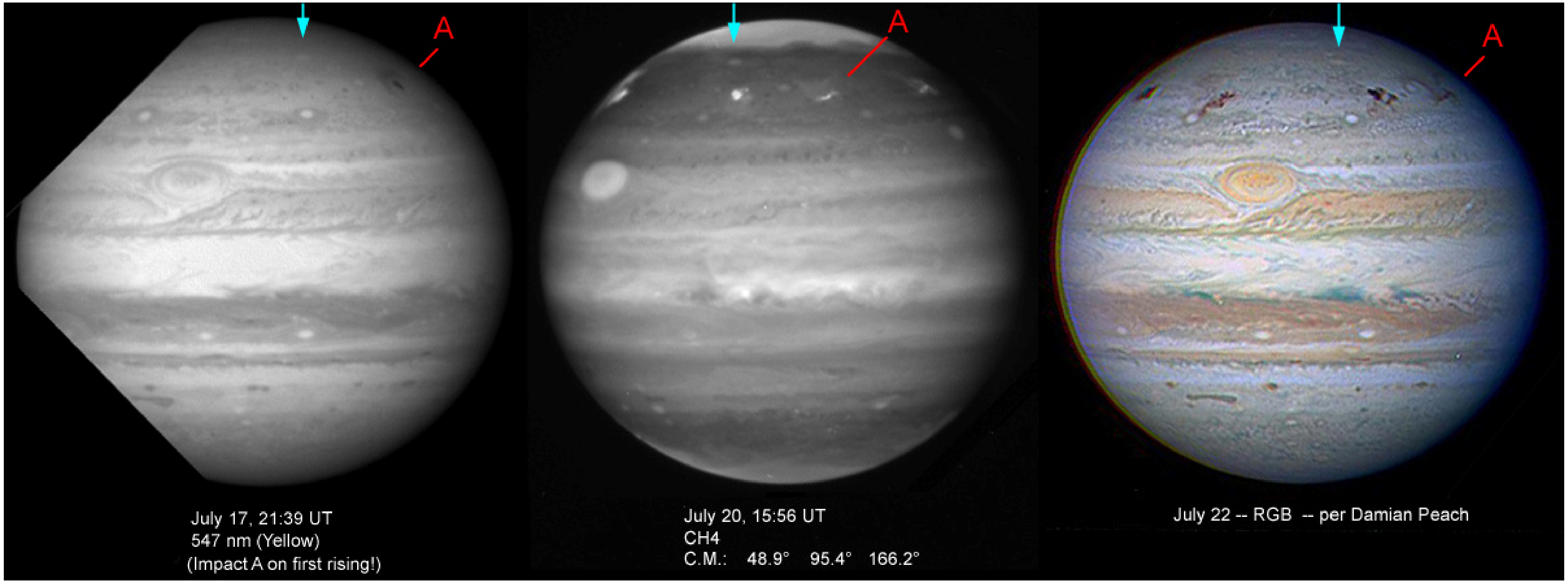
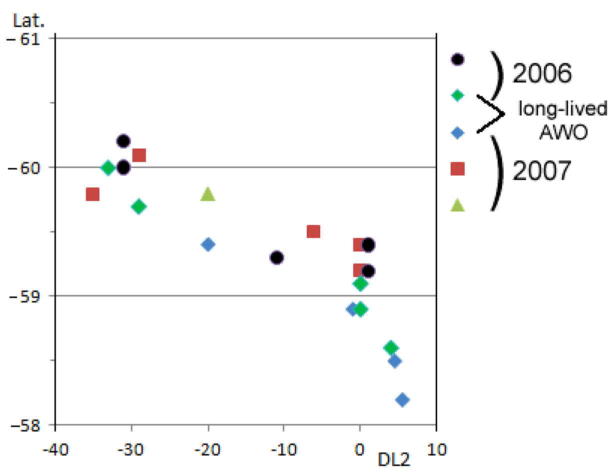
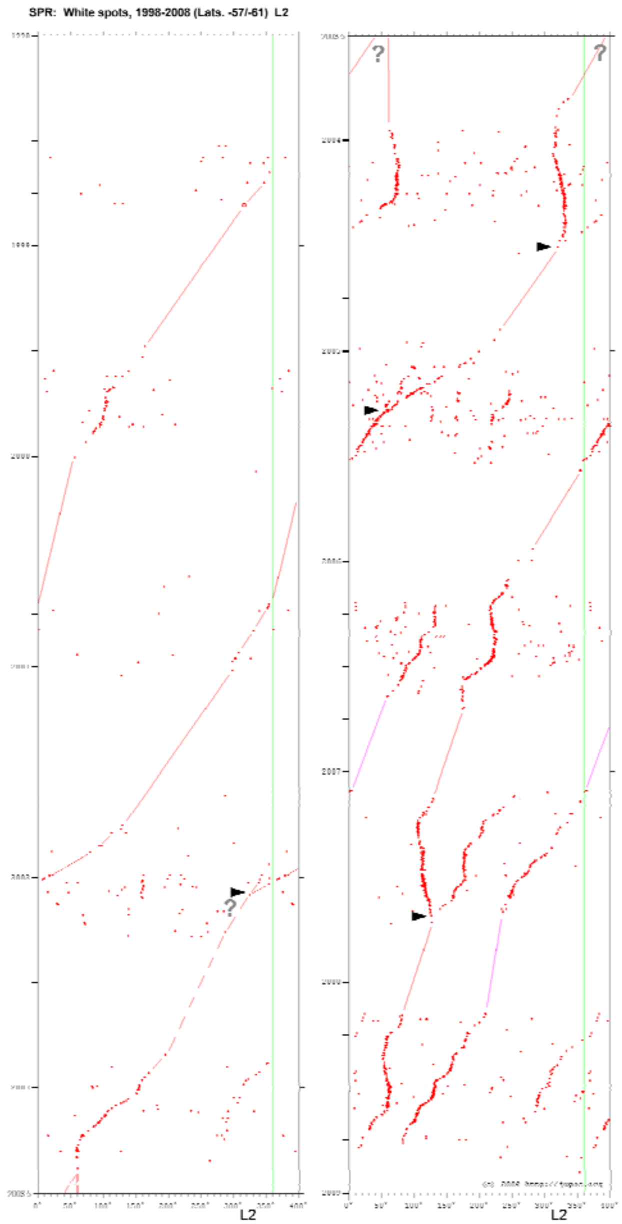


Fig.S8. Images of the SPR-WO in 1994 from HST (WFPC-2). These were taken during the Shoemaker-Levy 9 comet crash and show the first impact (A) and later impacts. **(a)** Yellow image, July 17, including impact A on its first appearance. **(b)** Methane image, July 20. **(c)** Colour image, July 22, compiled by Damian Peach with contrast enhancement. [Credits: Ref.34.]

Fig.S9A. History of the SPR-WO: Chart of longitude (L2) vs. time, for all bright spots between latitudes 57 and 61 deg.S, 1998-2008, from JUPOS records. Red connecting lines mark the probable track of the long-lived SPR-WO. Dark arrowheads indicate when it apparently merged with another spot.
Note 1: In 2001/02, the long-lived WO was not the one listed in the BAA report, but a small inconspicuous one with a very rapid drift increasing to -46 deg/mth. In 2002/03, the oval was well tracked (with oscillations), but in 2003/04 there were 2 such ovals and it is not clear which was the long-lived one. However, this does not matter for our purpose as they merged in mid-2004.
Note 2: Improved images in recent years allowed tracking of at least one other oval, which was smaller (purple connecting lines): it showed an oscillation with period 42-54 days throughout.

Fig.S9B. Correlation of latitude with speed for the SPR-WO (diamonds) and other white ovals in the SPR, from JUPOS data in 2006 and 2007 [Ref.14]. Each symbol represents one spot, with varying speed. The data agrees well with the Cassini zonal speed profile (not shown), and suggests that the long-lived SPR-WO (like NN-LRS-1) is centred at lower latitude than smaller ovals with the same speed.





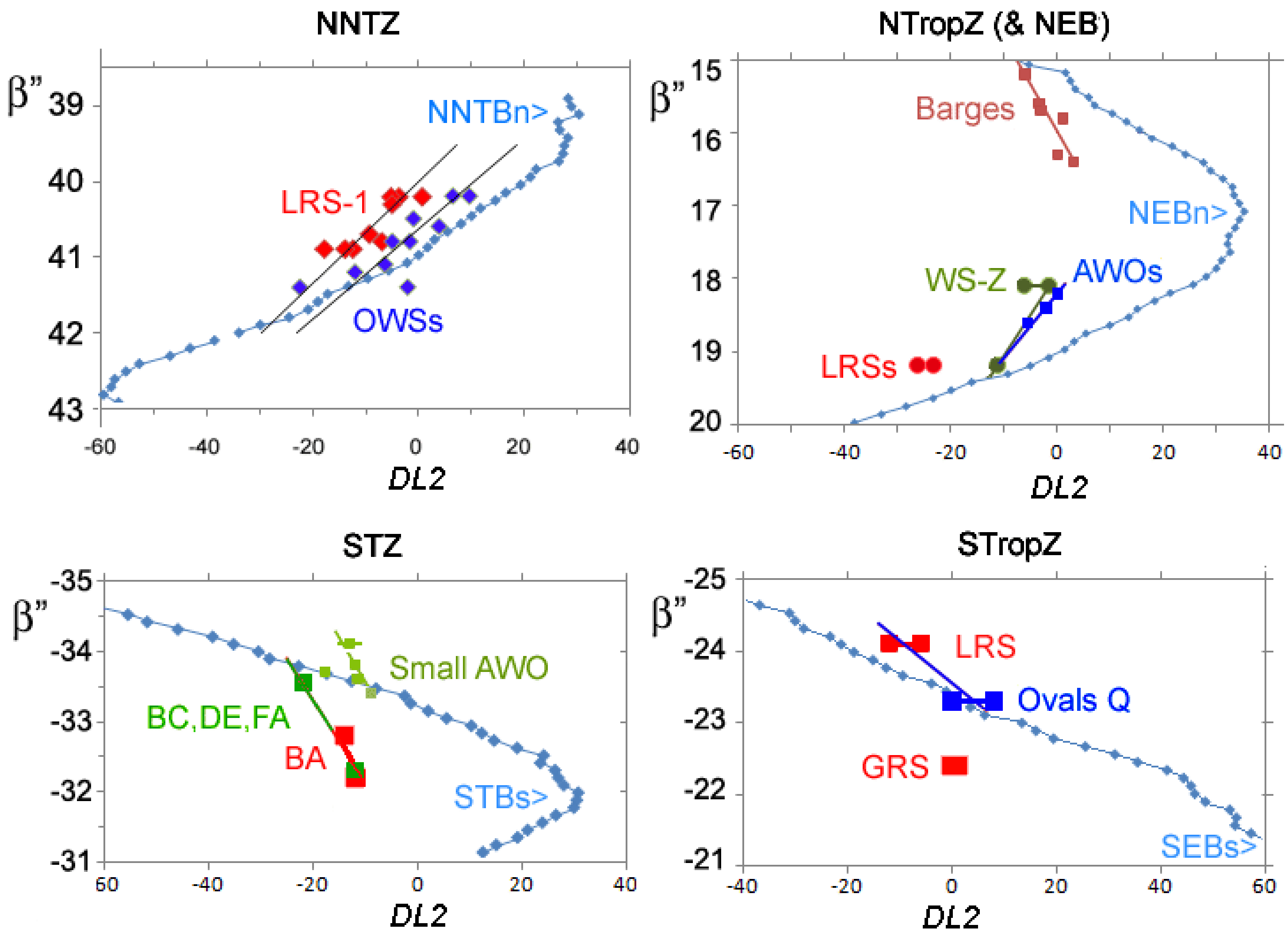


Fig.S10 [legend on next page]:

Fig.S10.

Comparison of NNTZ with other domains: Graphs of latitude (β") vs. speed (DL2), to compare zonal wind gradients with gradients for anticyclonic ovals which define 'slow currents'. Continuous blue line, with retrograding jets marked, is the Cassini zonal wind profile [Ref.25]. Other points are JUPOS/BAA data. Latitudes for the red ovals (red points) are given in **Table 5**; latitudes for other spots (dark blue and green points) from our 2007 report [ref.14] and other sources as listed below. (This is a preliminary analysis, based on only a few results from recent JUPOS/BAA reports (2000-02, and 2007), which need to be supplemented with data from the intervening years, not yet completed.)

NNTZ: this paper.

STZ: gradient for the great AWOs BC, DE, FA [ref.30]; oval BA follows the same gradient [refs.11,13,14,31]; the smaller AWO f. BA lies further S but has the same speed. Latitudes are for the visible centre; the dynamical centre defined by spacecraft wind tracking is slightly further S [ref.3 & refs. therein].

STropZ: Ovals Q (several years), and the LRS (2008), define a gradient for medium-sized anticyclonic ovals. The GRS lies further north, with little variation in DL2 and no confirmed variation in latitude.

NTropZ: both white spot Z and other AWOs follow a gradient [ref.14].

NTropZ LRSs in 1973 lie to the left of the 'AWOs' line on the chart, consistent with the other domains. (Cyclonic barges in the NEB also follow a gradient [ref.14] as noted previously [ref.20].)

Table 1: Observers using methane filters

Observer	*Location*	*Telescope*	*Filter/FWHM*	*Years*
Akutsu, Tomio	Japan	320-mm refl.	893 / 6.5 nm	2001-04
Akutsu, Tomio	Philippines	280-mm SCT	893 / 6.5 nm	2006-08
Cidadão, Antonio	Portugal	254-mm SCT & AO2	889 / 5 nm	2001-03
Cidadão, Antonio*	Portugal	356-mm SCT & AO2	889 / 5 nm & 18 nm	2004-08**
Colville, Brian	Canada	300-mm SCT	889 / 18 nm	2001-08**
Parker, Donald	Florida, USA	406-mm refl.	889 / 18 nm	2005-08
Peach, Damian	Barbados	356-mm SCT	889 / 18 nm	2007
Pujic, Zac	Australia	310-mm refl.	889 / 18 nm	2007
Yunochi, Kenkichi	Japan	260-mm refl.	***	2006-08

Notes to Table 1:
This table lists the principal observers using methane filters since 2000. Previously, see Ref.10.
In 2008, some methane images were also received from B. Gährken, C. Go, A. Kazemoto***, L. Owens, D. Peach.
SCT, Schmidt-Cassegrain: Peach’s 356-mm SCT was a Celestron-14", Cidadão's was a Meade LX-200.
Methane filters of width 18 nm were from Custom Scientific (Arizona): see transmission spectrum in ref.10.
This is the most popular filter as it allows exposures of only 1-2 sec, rather than 30-60 sec for a 5-nm filter.
Other filters were the same as used by these observers in Ref.10.
*Cidadão used adaptive optics and (in some years from 2004 onwards) greatly increased the sensitivity of his methane images by subtracting a rotationally-averaged ('mask') image.
**Not every year.
***Images kindly provided via the ALPO-Japan web site.

Table 2: The classes of ovals in the NNTZ

Name		*Example(s)*	*Colour*	*Methane-bright?*	*Size*	*Latitude***	*Duration****
LRS-1	Little Red Spot 1	LRS-1	Red to off-white	Yes	Largest	40.0	>15 yr
LRS-2	Little Red Spot 2	LRS-2	Red or sl. red	yes	Medium	nd	>= 3 yr
MB-WOs	Methane-bright white ovals$	WS-1, -4	White	Sometimes	Medium	40.3	4 or 5 yr
OWOs	Ordinary white ovals$	WS-2, -3, -5	White	No*	Smaller	40.6	2-3 yr
---	Minor white spots$	(not listed)	White	No*	Smaller	40.9	< 1 yr

$All these are anticyclonic white ovals (AWOs).

*except in v-hi-res images

**mean latitude for DL2 = 0, from regression line with gradient of 15 deg/mth per degree latitude.

***As members of each class can still be tracked in 2009, one year may be added to most of these entries.

Table 3: BAA/JUPOS records from BAA reports: NNTZ ovals

Appar'n	*Name*	*L2(O)*	*Colour*	*Notes*
	LRS-1			
1994	LRS-1	342	Reddish	
1995	LRS-1	315	Dusky reddish	
1996	LRS-1	186	Tiny orange oval	On Oct. 28, creamy-white
1997	LRS-1	67	Dark reddish (May), creamy or white (July-Nov.)	Imaged by Galileo (April) & HST, confirming colour change [Ref.15]
1998/99	LRS-1	347	White	
1999/00	LRS-1	270	Light or creamy-white	Oscillating, DL2 range -18 to -5 (P = 3-4 mth, 2 cycles)
2000/01	LRS-1	203	Light oval (pale fawn, = surroundings)	Still fluctuating with P = 3.6 mth: [Ref.11, Fig.11]
2001/02	LRS-1	166	Brick-red from Sep. to Feb; browner in Mar.	Ref.13: Long description: See Figs.16&17
2002/03	LRS-1	98	Not visible in RGB, (= surroundings)	
2003/04	LRS-1	150	Difficult in RGB; Reddish w dark rim	V.red (dark spot in blue) Merged with small AWO in May.
2004/05	LRS-1	33	Dull white (not reddish)	
2006	LRS-1	301	Light oval (pale fawn)	
2007	LRS-1	199	Dull reddish oval	
2008	LRS-1	85	Dull reddish light oval, dark rim	
	LRS-2			
1994	LRS-2	125	Reddish	
1995	LRS-2	16	Light reddish	
1996	LRS-2	34	Tiny orange oval	Weaker in Aug-Sep.(smaller, fainter, less coloured); not seen after Sep.9
	MB-WOs			
1997	WS-1	309	White	*Poss. = LRS-2?*
1998/99	WS-1	142	White	
1999/00	WS-1	19	White	Oscillating, DL2 range

				-14 to -1 (P = 3-4 mth, 2.5 cycles)
2000/01	WS-1	(280)	Bright white	(Still fluctuating with P = 3.6 mth)
				Last sighting: then merge with LRS-1?
2003/04	WS-4	193	White	Merged with smaller AWO in April.
2004/05	WS-4	190	White	
2006	WS-4	69	White	
2007	WS-4	311	Bright white	
2008	WS-4	233	White	

Table 4. Mean speeds of tracks spanning solar conjunction

	Limiting dates	*dur.(days)*	*DL2*	*DL2 range*
LRS-1	23.09.2001 – 20.04.2003-->	>579	0,0	-2.1 to +0.8
LRS-1	25.07.2005 – 8.03.2007	591	-9,1	-10.2 to -8.3
WS-1	31.07.1997 – 20.11.1999	842	-10,9	-13,6 to -8,3*
WS-3	18.11.2000 – 12.02.2002	451	+0.2	(poss. variation)
			*also short-term oscillations.	

Note to Table 4: These are tracks in which an oval maintained either fast or slow speed for more than a year; however there were usually some speed variations detected within these ranges, and oscillations could have occurred during solar conjunction.

Table 5: List of anticyclonic red ovals recorded on Jupiter since 1970

	Name	*Date-1*	*Date-2*	*Lat. (date)*	*Long-lived?*	*Large?*	*Fast-1?*	*Fast-2?*	*Notes*
(A) Long-lived stable ovals, sometimes red:									
STropZ	GRS	1831	1872	-22.4 (mean)	y	y	n	y	Similar, possibly the same, GRS observed 1665-1713.
STropZ	STr-WO	1987	1990, 1993	-23.3 (1994)	y	y	n	n	Single AWO [refs.32,33], became red in two separate years.
STZ	Oval BA	2000	2006	-32.8 (2007)	y	y	n	y	Oval BA formed in 2000 by merger of 3 white ovals which appeared in 1939-41.
NNTZ	NN-LRS-1, LRS-2		1993, 1994	+40 to +41	y	y	y/n	y	See text. (Miniature LRS in 2006 not included as it was so small.)
SPR	SPR-WO	1987	1994	-58 to -60	y	y	y/n	--	See text.
(B) Shorter-lived red ovals, possibly created in zonal recirculations:									
STropZ	(LRSs)		1986, 2008	-24.1 (2008)	n	n	y	n	Similar LRSs in 1986 and 2008, arose from S. Tropical Disturbances*
NTropZ	(LRSs)		1973, 1976	+19.2 (1973)	n	y	y	y	Two LRSs in 1973, another two LRSs in 1976. Origins unknown but similar non-red spots arise from disturbances in NEB.
NTZ	(LRS)		1997	+34.0 (1999)	y	n	y	--	**

Columns: Date-1: Date first observed, as a white oval.
Date-2: Date first observed as a reddish oval.
Lat: Zenographic latitude in selected apparition(s).
Long-lived?-- Y, >2 years; N, <~1 year.
Large?-- compared to other anticyclonic ovals in the same zone.
Fast-1?-- Did the LRS move fast compared to the slow current for its domain?
Fast-2?-- Did the LRS move fast compared to other features in the same latitude?

Notes to Table 5:

All these red ovals were anticyclonic and methane-bright. The table indicates whether they were notably long-lived, large, and fast-moving. Large, long-lived red ovals (like the GRS) move at similar speed to other ovals but are centred at lower latitude. Conversely smaller, shorter-lived LRSs are fast-moving compared to other ovals in the domain but only because they are at higher latitudes.

This is a preliminary table as data have not yet been compiled systematically for all these red spots and non-red spots in the same latitudes. Data are from Ref.21 and subsequent BAA/JUPOS analysis.

*Latitude for the STr-WO in 1994 is from Ref.33, and agrees with similar smaller ovals (Oval Q) in 1999-2002.

**The 1997 NTZ LRS arose at the p. end of a N. Temperate Disturbance, apparently by mingling of reddish clouds at or above cloud-top level [ref. 7]. It persisted to late 1999. A similar NTZ LRS was imaged in 1994 (see Appendix 2 & Fig.3).

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31. Adamoli, G., 'Ovali Temperati Sud di Giove', Astronomia UAI (2008) no.1, pp.22-24.
32. Chapter 10 of Ref.21, pp.197-198.
33. Sanchez-Lavega A. et 7 al., 'Dynamics and interaction between a large-scale vortex and the Great Red Spot on Jupiter'. Icarus 136, 14-26 (1998).
34. Hubble Space Telescope images from 1994: Credit to NASA, ESA, and the HST Comet Impact team, leader H. Hammel (MIT). Raw images were downloaded from the STScI on-line archive by Tan Wei Leong.
35. Hammel HB et 16 al. 'HST imaging of atmospheric phenomena created by the impact of Comet SL9.' Science 267, 1288-1296 (1995).
36. Network Cybernetics Corp., CD-ROM: 'SL9: Impact '94' (1994).
37. Sanchez-Lavega A et 7 al. (1998b) 'Long-term evolution of Comet SL-9 impact features: July 1994 – Sep. 1996' Icarus 131, 341-357 (1998).
38. Moreno F., Molina A. & Ortiz J.L. 'The 1993 SEB revival and other features in the jovian atmosphere: an observational perspective.' Astronomy & Astrophysics 327, 1253-1261 (1997). [Note: All figures are laterally reversed.]

Appendix 1: The NNTZ Little Red Spot in 1993

In 1993, amateur CCD imaging and methane-band imaging were in their infancy, so we do not have data to track LRSs thoroughly. Nevertheless we have searched available data for records of methane-bright (MB) spots in the NNTZ. Isao Miyazaki took the very first amateur images in the methane-band (0.89 μm), but they did not record any MB spot in the NNTZ. Some suitable hi-res images exist thanks to a joint professional and amateur International Jupiter Watch campaign in 1993 April, which coincided with the start of a SEB Revival. A set of maps from 1993 March to June at 0.89 μm, from Calar Alto and La Palma observatories, was published [ref.38]. They reveal a single major MB spot:

L2(March 30) = 21, DL2 = -8 deg/mth (March-May).

It was not visible on a blue image, nor in Don Parker's colour images, and was not recorded in amateur white-light images, so it was probably the same colour as its surroundings. (It should have been well observed as it was, coincidentally, due north of the SEB Revival.) This was clearly LRS-1.

The BAA report (J. Rogers & M. Foulkes, in preparation) does not record this oval, but does track 3 white ovals at other longitudes (dashed lines in Fig.2).

Appendix 2: The NNTZ Little Red Spots in 1994

In the 1994 apparition, there were two LRSs in the NNTZ. At that time, amateur data were still not sufficient to characterise them fully. Nevertheless, thanks to the world-wide campaign of observations for the comet crash, there were numerous publicly-released images from the Hubble Space Telescope (HST) and Earth-based infrared observatories (EIR), which clearly show that there were two methane-bright (MB) spots in the NNTZ which were both reddish ovals.

Many of these images have been measured for this report, as follows:

HST (WFPC2): Images from UV to IR including 0.89 μm methane band. [Refs.34,35] Exact longitudes were obtainable except for the Aug.24-25 images, where 6 deg. had to be added to all longitudes to agree with the positions of well-known spots.

EIR: Publicly released images from many IR observatories, either at 0.89 μm or in the range 1.7 to 2.3 μm, mostly from the CD [Ref.36]. Images from the following observatories were measured: Anglo-Australian Telescope, Calar Alto, Keck, La Palma, Lick, McDonald, NASA IR Telescope Facility. Also, a set of images at 0.89 μm from the Pic du Midi [Ref.37].

Almost all longitude measurements from EIR images were of low precision because they were done from reproductions on which the true limb was not visible and the exact time not stated, so the CM longitude was estimated from the positions of known features. However the measured positions mostly show good agreement, to within a few degrees.

Amateur, methane: Isao Miyazaki took images at 0.89 μm, which were among the first methane-band images by any amateur. Several of these show the NNTZ spots.

Amateur, visible: The BAA report for 1994 (M. Foulkes & J. Rogers, in preparation) notes several light ovals in the NNTZ. Some of them appeared to be pinkish in Don Parker's CCD images, including one at L2 = 190 (March 5) and 185 (March 20) which was probably LRS-2. Only one light oval was well enough tracked to give a drift: L2(0) = 345, DL2 = 0, lat. ~41 deg.N (5 obs'ns, May-July): evidently this was LRS-1. Several of Miyazaki's colour images clearly show LRS-1 as a red spot, giving accurate longitudes for it.

Combining all these measurements reveals the tracks of two LRSs:

LRS-1: L2(July 20) = 342, DL2 = 0
LRS-2: L2(July 20) = 125, DL2 = -14 deg/mth.

In HST images, LRS-1 was about 8 deg. long in I-band (bright), 6-7 deg. long in methane (bright), but smaller in blue and UV light (dark): i.e. the methane-bright oval had a smaller red core. LRS-2 was smaller: only 3-4 deg. long in I-band, methane, and blue light, though a rim ~5 deg. long can just be discerned. Thus LRS-2 was less bright than LRS-1 in methane images, even though the surface brightnesses may have been the same.

There was at least one other methane-bright spot in the NNTZ, as bright as LRS-2 in HST images, but only occasionally recorded in EIR images. It was at L2 =42 on Aug.24 (in visible light, a small ring with tiny bright core), and there was a pair at L2 = 37 and 55 in mid-July (both tiny white spots). It may also be the same as a pinkish oval at L2 = 50 in Parker's RGB images on March 10 and April 3, but there were no methane images then. As this spot was not adequately tracked, it is not considered further. HST may have detected this and some even weaker spots, not only because of its resolution but also because its 0.89 filter was not as selective as some others [ref. 10], thus probing deeper into the atmosphere.

HST and EIR and Miyazaki's CCD images also revealed a rare methane-bright LRS in the NTZ: L2 (July 20) = 319, DL2 = -4.5 deg/mth. (Fig.3 & S3). Both the occurrence and the drift of this spot seem to be very unusual for the NTZ, although another appeared in 1997 [ref. 7].