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

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As well as the Great Red Spot, Jupiter sometimes presents one or more Little Red Spots (LRSs) in various latitudes. An LRS is often seen in the North North Temperate Zone (NNTZ), but the frequency and properties of these ovals have never been studied in detail. Here we review all our records of the red, white, and methane-bright anticyclonic ovals in the NNTZ.

There is a simple conclusion: A single LRS, which we name NN-LRS-1, has persisted from 1993 to 2009. It has varied in colour between red and off-white, but has been methane-bright throughout these years. This now ranks among the most long-lived spots ever recorded on the planet. There is always at least one other oval in this latitude. This was a second methane-bright LRS from 1994–1997, and there was also a smaller LRS in 2006. The other ovals are all white; two have lasted for four years or more and were sometimes methane-bright; others have had shorter lives and were not. These results suggest that red colour, and the high-level haze that accompanies it, are correlated with the size and longevity of the oval.

All these ovals have variable speeds, alternating irregularly between slow (~ –1°/month in System II longitude) and fast (~ –12°/month). The latitudes of the ovals range from 40 to 41.5°N, and correlate closely with their instantaneous speeds. However the larger, longer-lived ovals (especially the LRS) are centred systematically further south than the smaller white ovals, because they distort the retrograding jetstream more deeply. Similar behaviour in other domains on the planet explains how ovals of different sizes move with a single slow current while also being sensitive to the zonal speed gradient.

An oval at 60°S shows very similar behaviour and has probably existed since 1994 or earlier.

Note: Parts of this paper are available as an online supplement at **www.britastro.org/jupiter/2009/NNTZ-LRS%20paper_Online-Supp.pdf**
This comprises: Figures S1 to S10 (Figures S1 to S6 supplement Figures 1 to 6 respectively);
Appendix 1: The LRS in 1993;
Appendix 2: The LRSs in 1994.

Introduction

There has recently been much interest in Little Red Spots (LRSs) on Jupiter.[1–3] These are a small minority of the anticyclonic ovals on the planet, and attract attention due to their colour and sometimes other exceptional features. Therefore we undertook this study to establish the history of the LRSs that are often recorded in the NNTZ, which have not been studied in detail. This entailed a full survey of the anticyclonic ovals at 40–42°N, the latitudes of the NNTZ.

Light ovals in these latitudes have commonly been recorded on high resolution images since 1973 (Figures 1 & S1).[4] The *Voyager* spacecraft recorded two such white ovals in 1979, at 41°N, ~5000km in diameter, plus one or two smaller ones.[4] From 1993 onwards, coverage has been much improved by hi-res amateur imaging[5–14] as well as occasional spacecraft imaging.[15–16] Usually there have been two to four well-defined ovals in this latitude range, and often at least one has been reddish.

Methane band images, e.g. at 0.89μm wavelength, record reflective high-altitude hazes, and certain anticyclonic ovals are always bright in methane-band images due to their elevated cloud caps: notably the Great Red Spot (GRS) and the great S. Temperate white ovals, and also at least some NNTZ ovals (Figures 1 & S1).[17] Since 1993, with regular methane-band imaging by amateur and professional observatories, there has always been at least one methane-bright spot in the NNTZ, and sometimes two. As we reported for 1997,[7] and have confirmed repeatedly since, in this and other anticyclonic domains, all reddish ovals (LRSs) and some anticyclonic white ovals (AWOs) are methane-bright; some AWOs are not (at least, not at the resolution of amateur images). Cyclonic ovals are never methane-bright.

However the long-term history of these ovals has not been evident, because they show a great range of drift rates subject to rapid changes which make long-term tracking awkward. Sometimes they move with the normal slow current for this domain, the NNTC, with drift rates in System II longitude (DL2) ~0 to –5°/month.[4] But sometimes they move faster, DL2 ~ –10 to –16°/mth.[4] These faster speeds are typical of the next slow current to the north, the N^3TC, and have

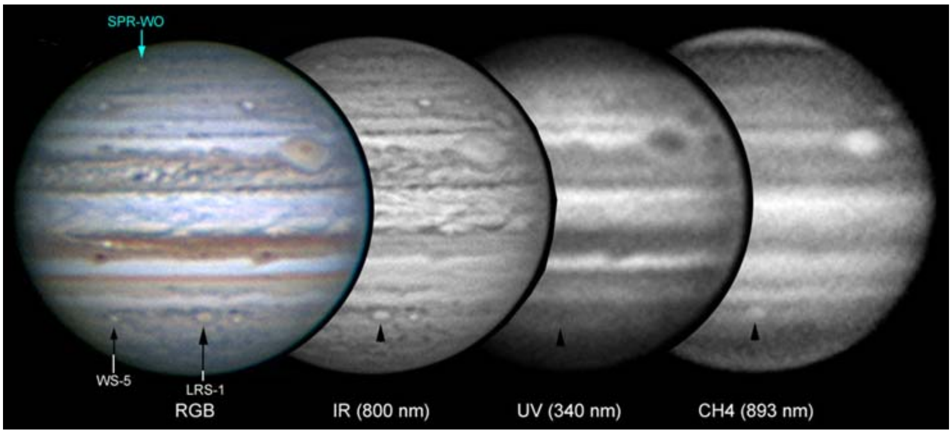

Figure 1. Multispectral images on 2008 May 24 by T. Akutsu, showing some of the NNTZ ovals discussed here (WS-5, LRS-1, and a minor AWO f. LRS-1). LRS-1 was reddish with a dark rim. Also note other reddish ovals: the SPR-WO, and the GRS and oval BA near f. limb (bright in methane image). (See Figure S1, online, for more images in 2008.)

been described as 'invasions' of the NNTZ by the N³TC. Sometimes a NNTZ oval switches from one speed to the other: one such switch was recorded in the *Voyager* coverage, taking only a few days.[4] The reason for these variations is unknown, but is probably correlated with changing latitudes of the spots. In this domain (unlike others), these mid-sized spots and streaks often show a gradient of speed with latitude from the NNTB to the N³TB, as shown for example in reports by the BAA,[8,11] and the Unione Astrofili Italiani.[18]

This study therefore aims to establish the long-term history of these ovals in the NNTZ, especially the LRSs and methane-bright (MB) spots. How long do these ovals last, and is there any pattern to their changes of colour, or drift rate, or latitude? To do this, we review all the relevant data collected by the BAA and the JUPOS project from 1993 onwards, and also include analysis from professional images in 1993 and 1994.

Methods

Figure 2 is a chart of longitude vs. time for all well-defined light spots and MB spots in the NNTZ (Figure 2 in System II; Figure S2 in System III). These are all anticyclonic ovals. The chart is compiled from the following sources.

Data for 1993 and 1994 are described in Appendices 1 and 2 (in Online Supplement). Data for subsequent years, all by our amateur contributors, were from the following sources, either in published BAA reports (1995–2002 & 2007)[5–14] or our unpublished analysis (2002 onwards). First, positions of white (or light) spots on visible-light images, measured either manually (1995–1998) or by the JUPOS project **(jupos.org)** (1998 onwards).[8] Second, manual measurements of the reddish and methane-bright spots in each apparition. The JUPOS project provided the majority of the data points for this project, but additional manual measurements were necessary because reddish spots often do not show up clearly on the charts as they are neither dark nor bright, and the JUPOS project does not include measurement of methane-band images.

The colour of each oval was estimated by visual inspection of images – usually colour images, and sometimes blue-light images – and the colour was categorised as follows:

- Reddish (redder than its surroundings; thus, darker than its surroundings in blue light);
- Slightly reddish (including pale fawn colour; this colour is often the same as the surroundings and the oval can only be distinguished by its outline on very-hi-res images, or even not at all as in 2003);
- White (usually bright, but dull white for LRS-1).

The first two categories are always methane-bright, and the white ovals divide into some that are methane-bright and some that are not. These four categories are colour-coded on Figure 2.

An oval was scored as methane-bright (MB) if it was visible in amateur 0.89μm images. There were always several suitable images, at least, per apparition from 1994 onwards. The types of methane-band image used have been described elsewhere (refs.7,10,12 & Table 1). The ovals are rarely resolved in these images (due to the long exposure times required), and most images have been subjected to local contrast enhancement techniques; therefore we cannot say anything about the surface brightness, although this could be assessed in images from the Hubble Space Telescope (HST) (Figure 3, Figure S3 & Appendix 2). A few ovals have been

Table 1. Observers using methane filters

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

Notes:
This table lists the principal observers using methane filters since 2000. For earlier years, see ref.10. In 2008, some methane images were also received from B. Gaehrken, C. Go, A. Kazemoto,§ L. Owens and D. Peach.
SCT= Schmidt–Cassegrain. Methane filters of width 18nm were from Custom Scientific (Arizona): see transmission spectrum in ref.10. Other filters were the same as used by these observers in ref.10.
* Cidadão used adaptive optics (AO) 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.

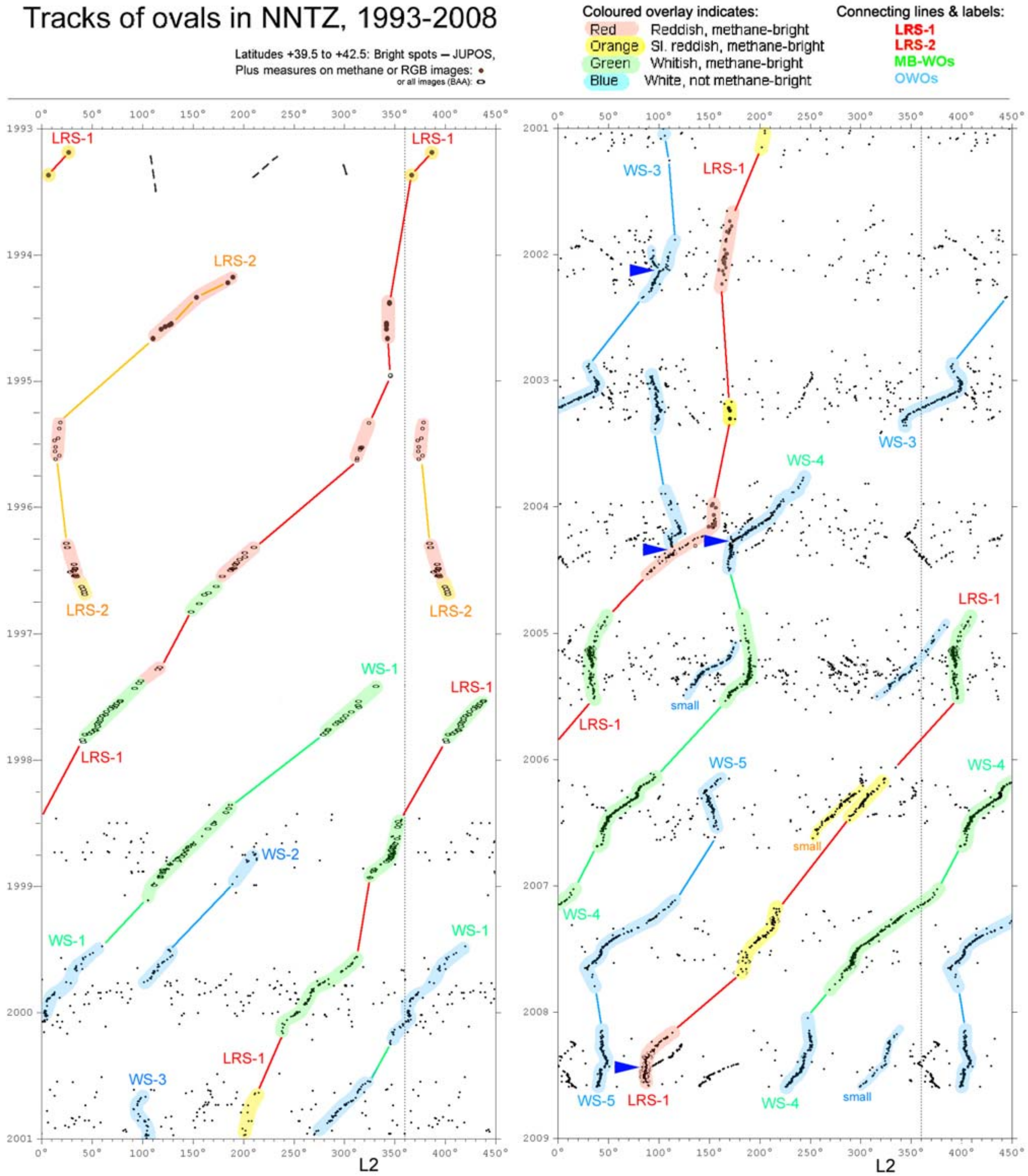

Figure 2. Chart of longitude (L2) *vs*. time, for all bright ovals between latitudes 39.5 and 42.5°N. Small points, JUPOS measurements; open ellipses, manual measurements on pre-1999 images; filled circles, manual measurements of red and/or methane-bright spots. Coloured overlay indicates whether the ovals were coloured and methane-bright (MB) at the time, thus: (pink), reddish and MB; (yellow), slightly reddish and MB; (green), white and MB; (blue) white and not MB (except in v-hi-res images). Colours of connecting lines and labels indicate the class of spot as in Table 2. Dark arrowheads indicate where ovals merged. (See Figure S2, online, for chart in L3.)

recorded reproducibly as 'weakly methane-bright', apparently because they are smaller than LRS-1. The other white ovals sometimes show up weakly in exceptionally hi-res methane images obtained with sophisticated processing (A. Cidadão) or with a broader filter (D. Parker), or from professional observatories or the HST, but their surface brightness is probably low (see Results).

We have not made systematic measurements of the sizes of the ovals because of the limited resolution of most amateur images, but they can be measured on hi-res images from spacecraft, and from some amateurs in recent years. These measurements were made on images from HST (1994–1997) and Damian Peach (2005–2007).

For analysis of drift rates and latitudes, from the JUPOS database we selected well-defined segments of tracks with constant speed (variations no more than 3°/month), lasting

Table 2. The classes of ovals in the NNTZ

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

Notes:
1 All these are anticyclonic white ovals (AWOs).
2 Except in v-hi-res images
3 Mean latitude for DL2= 0, from regression line with gradient of 15.0°/mth per degree latitude.
4 As members of each class were still tracked in 2009, one year may be added to most of these entries.

more than 25 days, with at least 5 observations per month. For drift rates, we also included a few tracks before 1998 when the measurements were not so frequent but interpolation appeared secure. For latitudes, pre-1998 data were not used, and the quality of data was carefully assessed to exclude values which were unreliable due to low resolution or other factors. Standard deviation of latitude measurements within a selected track segment was typically ~0.4 to 0.6°, indicating the typical precision of the JUPOS measurements. As large numbers of measurements were used, standard error was usually ≤0.1°. Latitudes are zenographic. All images are shown with south up.

Results

All ovals fall into four classes by colour, size, and longevity

To show how these ovals have behaved over many years, the records of colour and methane-brightness were superimposed onto the chart of longitude vs. time (Figure 2 in L2, Figure S2 in L3). All spots that were reddish, even if only weakly, were methane-bright (MB), as were some but not all of the white spots. The chart shows that the MB spots and reddish spots can be tracked over long intervals, in spite of sudden and unpredictable changes of drift rate. If the chart of bright spot longitudes were taken alone, there might be doubt about some of the connections made during solar conjunctions. However, the implied speeds during solar conjunction are all in the same range observed during apparitions, and any doubt about the connections is resolved when the colour and methane-brightness are taken into account.

The most important result is that one single MB LRS has persisted throughout these 16 years. It is here called LRS-1, or more generally, NN-LRS-1. It has always been MB, and its colour has varied several times from red to dull white. (It is never bright white.) There were few suitable images in which to search for it before 1993, so its actual longevity may be much longer than 16 years. In 1994, it was already larger and brighter than the other MB LRS, and since then it has always been the largest, or equal largest, oval in the NNTZ, averaging 7.5° (7260km) in length, with no sign of ageing (Figures 1,3,4,S3,S4). Measurements on images from HST (1994–1997), *Cassini* (2000), and Damian Peach (2005–2007) all show that the length ranges between 7 and 8° (6800–7700km), with no secular trend.

A second MB LRS in 1994 (LRS-2: Figure S3) was smaller, but nevertheless persisted to 1996. It may have transformed into WS-1 in 1997 but we cannot be certain from the chart. The only other LRS to be recorded was in 2006 only, and it was much smaller than LRS-1 (Figure S4), so will not be included in subsequent analysis.

The other long-lived ovals were all white (WS-1 to WS-5), and fall into two classes (Table 2). WS-1 (1997–2000) and WS-4 (2003 onwards) were MB in some years, so we class them as methane-bright white ovals (MB-WOs). Conversely WS-2 (1998–1999), WS-3 (2000–2003), and WS-5 (2006–2008) were never MB, except in a few very hi-res images: we call

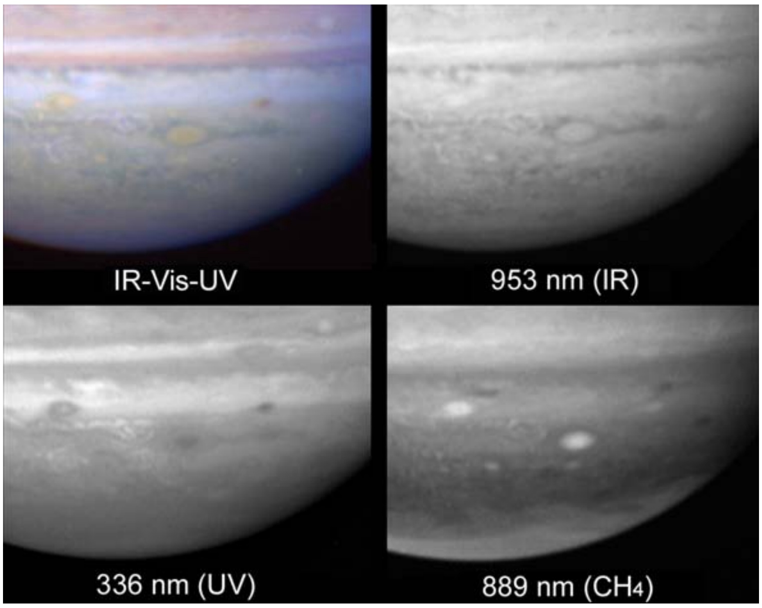

Figure 3. LRS-1 on 1994 July 30, from HST (WFPC-2), in multiple wavebands. It is bright in infrared continuum (IR) and methane (CH_4) but dark in ultraviolet (UV). The images are also combined to make an enhanced-colour image. At top left of each frame is another LRS, rapidly prograding in the NTZ, recorded only in summer 1994. (See Figure S3, online, for more HST images of LRS-1 and LRS-2 in 1994.) *Credits: see Ref.34.*

these ordinary white ovals (OWOs). The OWOs were shorter-lived than the MB-WOs, although again it is possible that one can evolve into the other (WS-3 may have become WS-4, and WS-5 has become weakly MB in 2009). In all the hi-res image sets which we have examined, LRS-1 is larger than the MB-WOs, which are larger than the OWOs (Figures 4 & S4). Some other white spots, probably smaller still, were tracked for no more than one year, and were not systematically included in this survey.

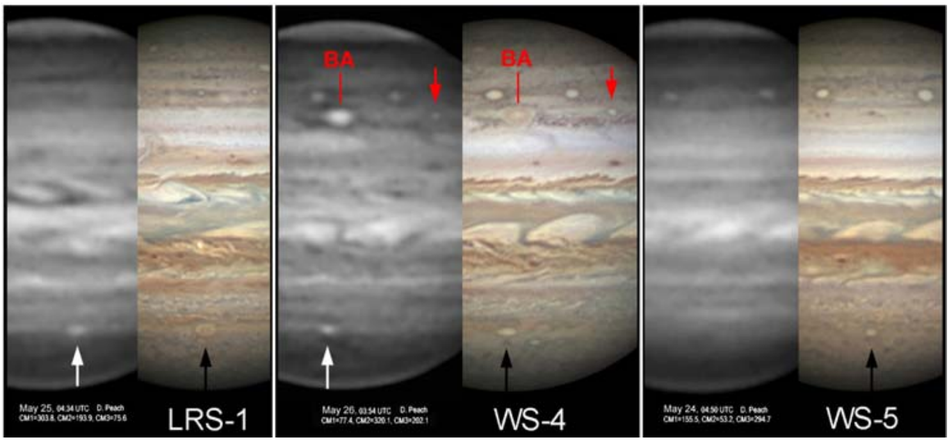

Figure 4. LRS-1, WS-4, and WS-5, in 2007: Methane-band and colour images by Damian Peach on Barbados. LRS-1 has a weakly reddish core. Note that WS-5 is not methane-bright although a slightly smaller S. Temperate oval is clearly detected (red arrow). Oval BA, and S.S. Temperate AWOs, are also methane-bright. (See Figure S4, online, for images in 2006.)

Thus all the ovals fall into four classes, summarised in Table 2, which represent a hierarchy of colour, methane-brightness, size, and longevity. The different classes are illustrated in Figures 4 & S4. The records of the LRSs and MB-WOs as noted in BAA reports are summarised in Table 3, which lists their position and appearance in each apparition. LRS-1 and LRS-2 were also well shown in published HST images and maps, in both colour bands and methane band, in 1995 and 1996[19] and 1994–2000.[15]

Drift rates have bimodal distribution

All the ovals show drift tracks with similar characteristics in Figure 2. Notably, the speeds appear to be bimodal. We therefore analysed the distributions of speeds and durations of all well-defined track segments in which a steady speed was maintained for >25 days (Figure 5 & Figure S5).

Indeed, for both LRS-1 and the MB-WOs, there is an unmistakable bimodal distribution to the speeds, with drift rates in L2 (DL2) concentrated around –2 and –12°/mth. The histograms of track segments show a minimum between –4 and –8°/mth: these intermediate speeds are uncommon (Figure 5A), and when they occur they do not last for very long (Figure 5C). (The longest recorded is 86d for LRS-1; most are much shorter). Indeed there are no drifts between 5.3 and –7.8°/mth. The mean speeds in the 'slow' and 'fast' ranges (below or above –7.5°/mth) are –1.3°/mth and –11.9°/mth. Within these ranges, both slow and fast track segments can persist steadily for >200d within an apparition, and indeed for more than a year when drifts are interpolated through solar conjunction (Table 4). There is no evidence for any preferred track length, but the histogram suggests that LRS-1 has more long tracks (>150d), both slow and fast, than any other ovals (Figure S5).

Where LRS-1 or MB-WOs appeared to show intermediate drifts on average through a whole apparition, this was always due to changes in speed – sometimes, regular oscillation between fast and slow track segments. Both LRS-1 and WS-1 showed oscillations from late 1998 to late 2000. These were especially pronounced and regular in 1999/2000, when both ovals showed periods of 3–4 months (though not synchronous) and amplitudes of 2–5°: LRS-1 was observed for 2 cy-

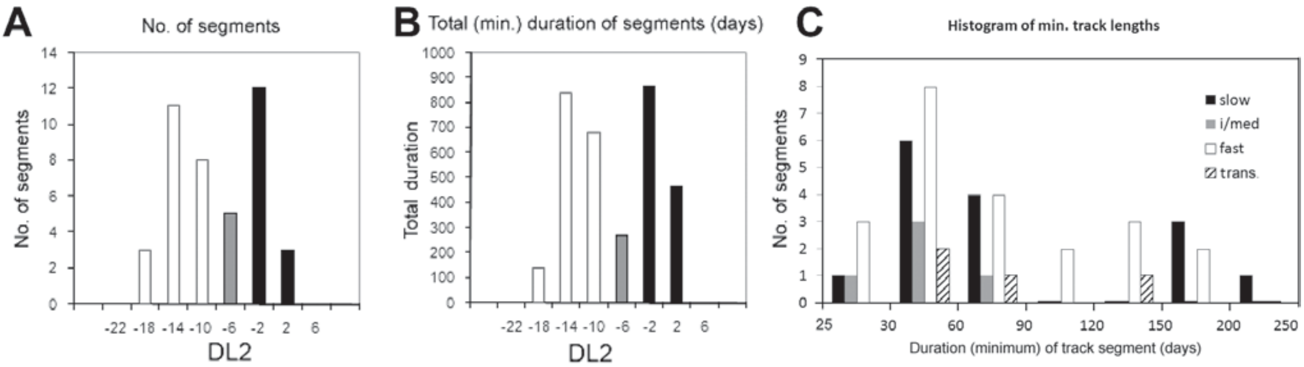

Figure 5. Histograms of drift rates (DL2, °/month), for LRS-1 and MB-WOs together (1996–2008). The charts include all track segments that could be identified with stable drift over >25 days. In many cases the duration was a minimum value, limited by solar conjunction or by other periods with few observations.

(A, B) Histograms of speeds of segments, by number of segments (A) or summed duration of segments (B). Each bin covers a range of 4°/mth centred on the stated value. Although not evident at this resolution, there are no drifts at all between –5.3 and –7.8°/mth.

(C) Histogram of (minimum) duration of segments, by speed range: slow (>–4°/mth), intermediate (–4 to –8°/mth), fast (<–8°/mth), or transitional (smoothly varying or oscillating so that no drift rate could be defined). Note that spots spend only a small amount of time in 'intermediate' and 'transitional' states. A small amount of time has been excluded altogether where observations were not sufficient to determine whether a spot maintained linear drift or not. Charts do not include tracks interpolated across solar conjunction (see Table 4). (See Figure S5, on-line, for histograms for each class of ovals separately.)

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[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, Figure 11
2001/02	LRS-1	166	Brick-red from Sep. to Feb; browner in Mar.	Ref.13: long description, see Figures 16 & 17
2002/03	LRS-1	98	Not visible in RGB, =surroundings	
2003/04	LRS-1	150	Difficult in RGB; v.red (dark spot in blue) till Feb., then reddish with dark rim. 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	*Possibly= 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	

cles, DL2 ranging from –18 to –5°/mth; WS-1 was observed for 2.5 cycles, DL2 ranging from –14 to –1°/mth. In 2000/2001, both still showed fluctuating drifts, which were consistent with the previous oscillations with a period of 3.6 months in each case, though with reduced amplitude. More recently, WS-4 has displayed oscillations throughout most of its existence, although without consistent period or amplitude; cycle lengths have ranged from 2 months to 4.5 months.

The changes in speed are often quite abrupt, occurring within only a few days, whether in the oscillating phases or in isolation. Where ovals had intermediate drifts on average through solar conjunction, of course, these may also have been due to switching between fast and slow track segments. The data do not show any obvious pattern to the changes in speed, and no correlation with the redness of LRS-1.

OWOs, on the other hand, show a broader range of drifts and little or no tendency to bimodality.

Mergers of ovals

Mergers between the named spots and smaller AWOs have been recorded on at least four occasions, indicated by arrowheads on Figure 2. One in 2002, between WS-3 and a smaller AWO f. it, was already reported.[13,20] The other events were in 2004 (when LRS-1 and WS-4 each encountered a smaller AWO p. it) and in 2008 (LRS-1 with a smaller AWO f. it). The 2002 event, like AWO mergers in the southern hemisphere, showed characteristic features of spiralling together, subsequent fast drift, and ejection of a retrograding cyclonic spot. However in the 2004 and 2008 events these features were not consistently seen and the fate of the smaller AWO

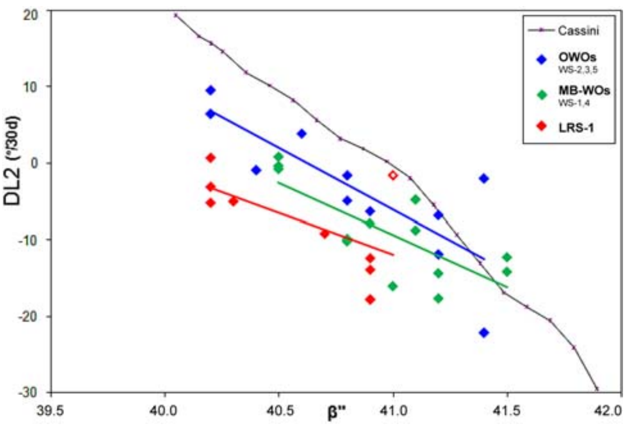

Figure 6. Chart of drift rate (DL2) vs. latitude (β"), for LRS-1, MB-WOs, and OWOs (1998–2006). The 3 classes of spots follow approximately parallel regression lines. The continuous line is the *Cassini* zonal wind profile.[25] The outlying point for LRS-1 (red open symbol) is from 2001/'02, when the spot was unusually dark red in a light zone. See Figure S6 for a regression line with this point excluded, and with minor white spots added.

was not clear – perhaps because of the size difference. It may be significant that the named ovals have only merged with minor ovals, but when long-lived ovals approached close to each other, they moved away again – behaviour which parallels that of the ovals in the South Temperate region through most of their history.

Latitude variations

In most domains on Jupiter, substantial ovals such as these normally show only small variations in speed, adhering to a single 'slow current' even if they vary in latitude.[21] However in the NNTZ, we have repeatedly noticed that these ovals tend to move faster when they are further north, and there is evidence for a gradient of speeds across the NNTZ.[4,11,18] We have therefore analysed the latitudes and speeds of all these ovals throughout this data set, taking all track segments where an oval maintained a well-defined speed for >25 days.

All the ovals show a clear correlation of speed with latitude (Figures 6 & S6A), consistently from 1998 to 2006. But, notably, LRS-1 is systematically centred further south than the MB-WOs, which in turn lie further south than the OWOs.

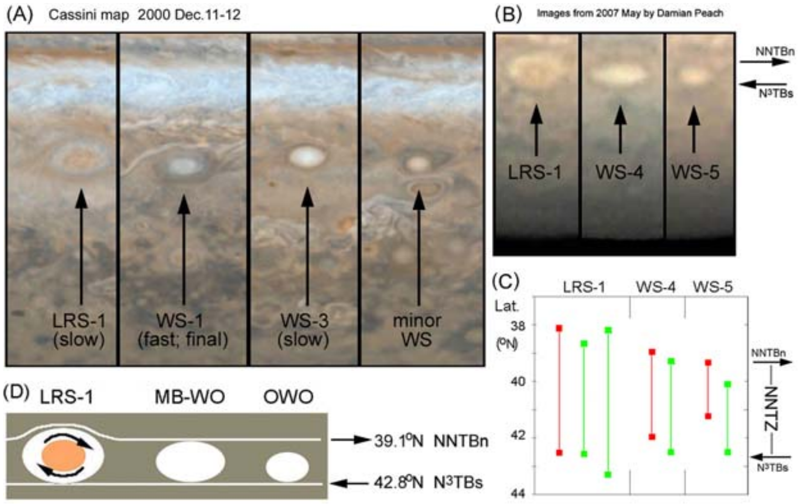

Figure 7. Alignment of the ovals in latitude.
(A) *Cassini* map (2000 Dec.). NASA/JPL/University of Arizona image PIA07782, from the *Cassini* ISS team, leader Dr C. Porco *(CICLOPS/SW Res.Inst., Boulder).*
(B) Images by D. Peach (2007 May, from Figure 4): all 3 ovals were moving fast at the time.
(C) Measured latitudes of S and N edges of LRS-1, WS-4 (MB-WO), and WS-5 (OWO), from images by HST (1994; first column for LRS-1 only: n=4) and D. Peach (2006: n=3 or 4, and 2007: n=1 or 2). Red symbols when the oval had slow drift, green symbols when it had fast drift. Note that LRS-1 is broader than the NNTZ and always indents the NNTBn jet, whereas the white ovals are as wide as or narrower than the NNTZ. When they are moving fast, all are positioned with the N edge at the N³TBs jet, but when they are moving slowly, the white ovals shift bodily to the S.
(D) Diagram showing relation to jets. Typically, the north edge of each oval is close to the prograding N³TBs jet. In (A), WS-1 was unusually further north than the other ovals, because it was drifting faster and, perhaps, because it was at the end of its life. This was the last image of it, and the outer part of the oval has become dark grey. In (B), the relative latitudes of the ovals are shown when all 3 had fast drifts, approximately aligned with the adjacent jets. This is the typical arrangement as summarised in (D).

All the ovals show a good fit to a linear equation of the form:

$$DL2 = -15.0\,(B'' - Bo)$$

where DL2 = drift in L2 in degrees per 30 days, B" = zenographic latitude, and Bo = 40.0 (LRS-1), 40.3 (MB-WOs), 40.6 (OWOs), 40.9 (minor white ovals lasting <1 year). The mean gradient is –15.0°/mth per degree latitude (±1.2: standard error of the mean). The individual regression lines (Figure S6A) do not differ significantly from this value.

This means that larger, longer-lived ovals are centred at lower latitudes, for any given speed. This relation is shown directly in Figure 7. For all the ovals, when they are moving fast, the north edge is adjacent to the prograde N³TBs jet, and the south edge is at a variable distance from the retrograde NNTBn jet. The white ovals span part or all of the NNTZ, while LRS-1, being larger, indents the NNTBn jet substantially, no doubt diverting it around the oval (in the same way that the GRS forms the Red Spot Hollow). When the white ovals are moving slowly, they shift bodily to the S, up to or perhaps slightly into the NNTBn jet.

The speed gradient for these ovals is in the same sense as the zonal wind gradient as measured by spacecraft (~ –24°/mth per degree latitude), but only about half as steep. These properties of the speed gradient are also seen in other domains on the planet (see Discussion below).

When the speed of an oval changes abruptly, the latitude changes simultaneously, within the precision of measurements (e.g. Figure S7). (Because measurements on several dates are needed to provide a sufficiently accurate value, the latitude cannot be reliably established over intervals of less than 5 days.) Sometimes the ovals oscillate in speed (e.g. in 1999/2000), and the latitude–speed relation holds over the shortest intervals that we can measure, with no perceptible delay. (Another example of this was the small LRS in 2006, not included in the data sets presented, which oscillated along a trend line between those of the MB-WOs and the OWOs.)

Table 4. Mean speeds of tracks spanning solar conjunction

	Limiting dates	*Dur.(days)*	*DL2*	*DL2 range*
LRS-1	2001 Sep 23–2003 Apr 20	>579	0	–2.1 to +0.8
LRS-1	2005 Jul 25–2007 Mar 8	591	–9.1	–10.2 to –8.3
WS-1	1997 Jul 31–1999 Nov 20	842	–10.9	–13.6 to –8.3*
WS-3	2000 Nov 18–2002 Feb 12	451	+0.2	(poss. variation)

*also short-term oscillations

Note: 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.

A few points lie unusually far north and may indicate special conditions. First, LRS-1 was very far north in 2001–2002 (the outlying point at 41.0°N in Figure 6), when the spot was unusually dark red with the NNTB absent.[13] The same appearance has recurred in 2009, and again the spot is unusually far north (data not shown). These latitude values are essentially the same whether it is measured as a dark spot in visible light or a bright spot in infrared, so they appear to be reliable values for the whole

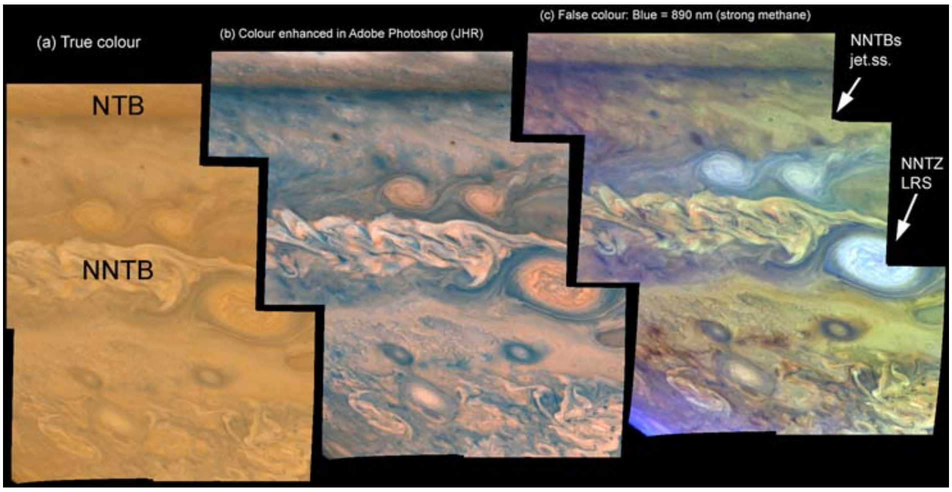

Figure 8. LRS-1 from *Galileo* Orbiter (G7 perigee, 1997 April). **(a)** True colour. **(b)** The same with colour enhanced to show relative differences: NN-LRS-1 is redder than other spots. **(c)** False colour: 889nm (strong methane) in blue, 727nm (weak methane) in green, 756nm (red) in red. NN-LRS-1 is MB so appears white indicating that it is covered with thick high-altitude clouds. The image also happens to include a pair of NNTBs jetstream spots, which are shown to be anticyclonic vortices which are slightly reddish and MB. NASA images PIA00893 & 894, taken by the *Galileo* SSI team, leader Dr M. J. S. Belton. Available at **http://photojournal.jpl.nasa.gov/targetFamily/Jupiter**.

LRS. It is thus possible that LRS-1 may move exceptionally slowly for its latitude when it has this appearance. (Likewise, the GRS moves exceptionally slowly when it is dark red and the surrounding belt has brightened.)

Secondly, there is some evidence that ovals lie anomalously far north at the end of their lives, as the last points for WS-1, WS-3, and two minor ovals, are the points that lie furthest to the right of the regression lines in Figures 6 and S6. (See image of WS-1 in Figure 7A, and data for WS-3 in Figure S7.)

Data for 2007–2008 are plotted separately (Figure S6B), and show similar correlations, but surprisingly the regression lines for LRS-1 and MB-WOs are all ~0.4° further north. The reason for this is not yet clear. There has been no obvious change in the quality of images or data analysis at this time, and a similar analysis of the NNTBs jetstream spots in 2006 and 2008 shows no such shift (data not shown). It is therefore possible that the difference for the NNTZ ovals is real, perhaps due to a shift in latitude of one of the jetstreams. In this paper we adopt the pre-2007 results. In any case, the difference is small, and does not make any difference to our conclusions.

A similar oval in the South Polar Region

Since 1994 there has always been at least one bright oval at ~58–60°S (Figures 1, S1 & S8), and it is likely that this has been a single oval throughout. Tracking it is less secure than for the NNTZ ovals, because it is smaller, less readily detectable in methane images, and has even more extreme changes of drift rate (Figure S9A). Therefore there are years when the continuity of the track is uncertain, but it is likely to be a single oval. Our long-term records of it extend back to 1996, and it may be identical to a similar spot recorded over one month in 1995 (BAA) and in 1994 (HST: Figure S8). Indeed, Morales–Juberias *et al.*[15] reported that they had tracked this oval from 1987 to 2000, so it is now 21 years old. It is in an anticyclonic domain, and may even be the same 'grand spiral' that was imaged by *Voyager* in 1979, which had the typical morphology of an AWO[22,23] (despite a perplexing measurement in ref.23).

This oval shares all the key properties of NN-LRS-1:

– It is long-lived (probably at least 1987–2008).
– It is the largest oval in its domain. (3500×3200km)[15]
– It shows large and sudden changes in drift rate, ranging from DL2 = +5 to –46°/mth.
– In some years its motion is oscillating. (Other ovals, when present in the same latitude, show similar drift behaviour and even more regular oscillations, with periods 42–66d.)
– It drifts faster when at higher latitude (Refs.9&14; Figure S9B). There is no perceptible lag between changes in drift and latitude. The graph (Figure S9B) suggests that it lies at lower latitude than smaller ovals in the same region.
– Sometimes it apparently merges with a smaller white oval either p. or f. it (arrowheads on chart), although given the small size of the spots we have never been able to resolve one of these mergers directly.
– It is usually yellow or slightly reddish (in contrast to similar white ovals at 50°S), though never strongly coloured.
– It is methane-bright, as shown in HST images in 1994 (Figure S8), and some hi-res amateur images from 2007 onwards, although much less conspicuous than NN-LRS-1 (not only because it is smaller, but possibly also because its high latitude makes it more foreshortened and more susceptible to upper atmospheric absorption).

Discussion

We already know that, among the anticyclonic ovals in this latitude, some white ovals and all reddish ovals (however slightly reddish) are methane-bright. The present analysis also reveals that LRS-1 (more generally named NN-LRS-1) is also the largest and longest-lived, and that all the ovals can be categorised as in Table 2, showing a hierarchy of colour, of methane-brightness, of longevity, and of size.

Is it possible that all these ovals are MB, but amateur methane-band images fail to detect the smaller ones? Indeed the MB ovals we detect are the larger ones, and LRS-1 is the largest. Higher-resolution images at 0.89µm do sometimes detect smaller ovals in the NNTZ and N^3TZ – especially HST images (Refs.15, 19, & Appendix 2), but also recent amateur images by A. Cidadão, D. Parker and D. Peach (albeit these HST and amateur filters are not the most selective[10]). Whether there are any differences in surface brightness has not been reported. Recent v-hi-res amateur images indicate that there are real differences. Thus in 2006, a small reddish oval was detectably MB, while similar-sized WS-5 was not (Figure S4). Again in 2007, WS-5 was not detectably MB even though an oval of the same size in the STZ was detected (Figure 4).

Spacecraft observations

LRS-1 has been observed by several spacecraft during its long life. HST images from 1994–2000 were reviewed by Morales–Juberias *et al.*,[15] who noted that LRS-1 had existed throughout these 6 years. Their Figure 3 illustrates LRS-1 in hi-res HST images in methane, IR, and blue wavebands, showing its transition from red (1995 Oct.5 & 21) through slightly reddish (1997 April 4) to white (1997 Nov.6). Its size did not change. (Their Figure 2a also illustrates a smaller spot, presumably LRS-2, in 1996 May.) LRS-1 and -2 were also well shown in global maps of methane-brightness and redness, compiled from HST images, in 1995 and 1996.[19]

LRS-1 was targeted by the *Galileo Orbiter* in 1997 April, although due to its unpredictable changes in drift, only half of it was imaged, and only on one rotation (Figure 8).[24] LRS-1 was also well shown in *Cassini* images.[11,25]

What determines whether an oval becomes red?

We have shown that the larger ovals in the NNTZ are longer-lived and methane-bright, and the largest and longest-lived of all is sometimes red. These correlations are with longevity (durability), not age. NN-LRS-1 has not become larger or redder with time. We do not know how old it is, but there has been no systematic trend in its properties since it was first detected in 1993.

Red ovals in other domains, notably the GRS and Oval BA, are also the largest and longest-lived anticyclonic ovals, and we propose that this is the reason for their tendency to redness. As with the NN-LRS-1, this does not mean that such ovals become larger or redder as they become older – indeed they tend to shrink over the years. But whereas the long-lived S. Temperate AWOs were almost always white, their merger to form oval BA created a larger oval, which may be why it became reddish a few years later. Some smaller ovals which transiently became reddish are also exceptionally long-lived and comparatively large for their domains, in the STropZ and SPR (Table 5). For all of these ovals, the red colour is variable. Even the GRS has sometimes lacked it over historical times, and in all the others it has varied from year to year. Also it does not necessarily fill the whole oval; for each of these ovals the red colour is sometimes confined to a smaller oval within it.

However not all red ovals are large and long-lived (Table 5): some have been small and short-lived. These examples were all rapidly prograding in their zones, and there is evidence

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,[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	SP-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	–	**

Notes: All these red ovals were anticyclonic and methane-bright.
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?
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.[7] It persisted to late 1999. A similar NTZ LRS was imaged in 1994 (see Appendix 2 and Figure 3).
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.

that they may have arisen from vigorous local eddying. We discuss below why red colour may appear for a variety of reasons in jovian spots.

Also, the general correlation with size and longevity does not explain why the redness of NN-LRS-1 changes from year to year. A 7-year periodicity is possible (peak redness in 1994–'97, 2001–'02, 2009), but would not be convincing unless confirmed over further cycles. Review of the data does not reveal any correlation of NN-LRS-1's redness with:

– size (no variations detected);
– speed (see Figure 2);
– mergers (in 2004 and 2008, and possibly 2002);
– darkness of NNTB;
– NNTBs jetstream spot activity (major outbreaks from 1993–'94, 2000–'01, and 2003–'06).

The nature of red colour on Jupiter

Reddish colours on Jupiter are associated with regions notable for their strong winds or turbulence, from the largest to the smallest scales.[2,3,26,27] Reddish colour is seen on:

– the largest anticyclonic vortices (GRS and LRSs: Table 5A) and rare smaller anticyclonic vortices (Table 5B);
– the fastest jets (NTBs and across the EZ), intermittently, especially in association with global upheavals;[21]
– various belts and zones after large-scale turbulent outbreaks such as SEB Revivals, NEB expansion events, and jetstream spot outbreaks;[21]
– tiny eddies in turbulent cyclonic regions (in spacecraft images: ref.27, and Figure 8);
– cyclonic dark barges as they disappear.[2,13]

Although the reddish colour is a high-altitude haze – probably a thickening or darkening of the violet-absorbing haze that is widespread over the planet[26] – its association with energetic phenomena in the underlying clouds has long been taken to imply that the red material is brought up from a deep level: either an intrinsically red substance, or a compound which turns red on exposure to UV light at high altitude.[27,28]

From this analysis of NNTZ ovals, we have concluded that the redness of an oval is correlated with its size and its longevity. This prompts further speculation to link two prevalent conjectures about the planet's anticyclonic ovals:

1) That the red material is something dredged up from a deep level; hence, red ovals extend deeper than others.[27]

2) That stable ovals penetrate deep:[29] new-born circulations and jetstream spots begin as shallow eddies, but penetrate deeper as they mature, and become anchored in deep flow patterns which determine the standard slow currents.

Thus a long-lived large oval, such as NN-LRS-1, or the GRS, or oval BA, has acquired deep roots which raise some chemical in the updraft, which is (or becomes) red when exposed at the cloud-tops. This may be related to high wind speeds in the oval,[3] although these have only been well documented for the GRS.

Shorter-lived LRSs in the STropZ, NTropZ, and NTZ (Table 5) have probably arisen from vigorous recirculations: e.g. recirculations of jetstream spots at S. Tropical Disturbances, or extensive disturbance in the NEB that creates large eddies in the NTropZ. These may be vigorous local eddies which extended rapidly to great depth, and thus became red.

Drift rates in NNTZ alternate between fast and slow

All of the NNTZ ovals show variable drifts, and this analysis documents what was already suspected:[4] that drifts of the larger ovals tend to be bimodal, with DL2 either close to zero (mean = –1.3°/mth: N.N. Temperate Current) or DL2 ~ –12 (mean = –11.9°/mth). All the long-lived ovals – both NN-LRS-1 and the MB-WOs – vary their drifts between these two ranges. (Smaller, shorter-lived white ovals have speeds across the same range but with a greater scatter.)

There does not seem to be any pattern or predictability to the speed changes. Sometimes an oval maintains either fast or slow speed for 1–2 years; sometimes it switches unpredictably and suddenly between the two ranges; and sometimes it oscillates between them with a period of a few months.

Historically, in most domains on Jupiter, most medium-to-large features have been observed to have almost constant speeds – the 'slow current' for each domain.[21] The broad and bimodal speed distribution in the NNTZ is an exception to the general rule. Can this be explained? In the past the faster speeds have been interpreted as 'invasions' of the NNTZ by the current that governs the next domain north (N^3TB); however, recent hi-res observations have shown no evidence that the fast speeds are induced by any activity in the N^3TB. Rather, they depend strictly on the latitudes of the ovals, which may indicate that ovals have greater freedom to wander in latitude in the NNTZ than in other zones.

Latitude variations: Comparison of the anticyclonic ovals in NNTZ and other domains

These results advance our understanding of the relationship between drift rates observed at different scales, which has long been puzzling. Spacecraft tracking of the zonal winds – i.e. the average wind at each latitude, revealed by small cloud-top features – reveals a 'zigzag' pattern of continuous gradients across every domain on the planet. In contrast, long-term tracking of substantial spots, which are coherent circulations, shows that they adhere to the 'slow current' for their domain in spite of differences in size and latitude. Hi-res observations of smaller spots, both from spacecraft (e.g. ref.16) and our recent analyses (e.g. refs.14,20), do show intermediate speeds which partially follow the zonal wind gradients. Whereas this behaviour has been interpreted in terms of wave motion opposite to the zonal winds,[15,16] the more straightforward interpretation is that coherent spots are intrinsically slow-moving but smaller ones are weakly entrained by the zonal winds.

The NNTZ differs from this paradigm in that even the larger ovals here have variable speeds which show a gradient with latitude across the domain. The present results reconcile and generalise these two paradigms for the NNTZ:

(i) such ovals do generally follow gradients, but

(ii) these have much shallower slopes than the zonal wind gradients; and

(iii) larger ovals (including red spots) follow a gradient displaced to lower latitude, as they are centred closer to the retrograde jet than the smaller ovals (Figure 7), so the average speeds for large and small ovals are about the same.

A preliminary survey suggests that the same conclusions apply to all the major anticyclonic domains where large ovals are observed: NNTZ, STZ, STropZ, and NTropZ (Figure S10). In each case, medium-sized ovals follow one gradient much shallower than the *Cassini* zonal wind gradient, while large ovals have lower latitude and/or faster speed. These larger ovals – NN-LRS-1, the NTropZ LRSs of 1973, the GRS, and the great S. Temperate WOs – all distort the flanking jets in the same manner, digging deeply into the retrograde jet and only slightly deflecting the prograde jet – as shown in Figure 7. It is possible that the ovals broaden and increasingly deflect the retrograde jet as they get older. There is some evidence for this with ovals BC/DE/FA,[30] but further details would be beyond the scope of this paper. Even though the large ovals thus intrude deep into the adjacent belt, they still drift as though confined within the zone like smaller ovals. This probably happens because they perturb the local flow around them (as in the Red Spot Hollow), stretching the wind speed gradient to match the N–S width of the oval rather than just the zone, so the zonal average wind speed gradient does not actually apply around the large oval. This behaviour explains how ovals of different sizes move with a single slow current while also being partially sensitive to the zonal speed gradient.

It is still unclear why ovals in the NNTZ, unlike other zones, are free to move through such a large range of latitudes and speeds, and indeed to alternate between two ranges of favoured speeds. This seems surprising as the jets and gradients in this domain do not appear unusual, and the larger ovals fill the entire width of the zone or more. However such behaviour is more common in higher-latitude domains, e.g. at 50°S as well as 60°S, so it could relate to global properties of deeper levels that we so far have no way of probing.

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