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Jupiter's southern high-latitude domains: long-lived features and dynamics, 2001-2012

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References & Figure legends are at the end of this file.

Tables and Appendices are in a separate file. (Some Tables are also inserted into this text.)

Figures are in a separate PDF file (miniatures) and ZIP file (full-size).

***Abbreviations used*:**

AWO, anticyclonic white oval	GRS, Great Red Spot
F., following = planetary west (right in images)	P., preceding = planetary east (left in images)
ZDP, zonal drift profile	ZWP, zonal wind profile
SSTB, South South Temperate Belt	SSTZ, South South Temperate Zone

--and other standard abbreviations for belts and zones, given on the BAA web site under 'Programme'.

Summary

Here we present an overview of the three domains in high southern latitudes of Jupiter, from 36 to 61ºS. Domains are defined as latitude bands bounded by prograde jets, and we propose a simplified nomenclature for the high-latitude domains and jets. We survey the dynamical characteristics of the S2, S3, and S4 domains, and of the S2, S3, and S4 prograde jets on their north edges. We also summarise the long-term history of the major features, especially the long-lived anticyclonic ovals.

This report covers the years 2001-2012, from the JUPOS database, with more limited summaries of some aspects back to 1986. We analyse the drift rates and latitudes both for long-lived ovals and for many smaller, short-lived features. These establish speed-vs-latitude relations for these spots (Zonal Drift Profiles, ZDP) over most of the latitude range considered. At these high latitudes the ZDPs are close to the Zonal Wind Profile (ZWP) derived from spacecraft imagery.

The most conspicuous and long-lived features of these domains are anticyclonic white ovals (AWOs). In the S2 domain (S.S. Temperate domain; 40.5ºS), from 1986 to 2012, there were always 6-9 long-lived AWOs, among which three disappeared (probably all by mergers), five appeared, and three or four have survived the full 27 years. There seems to be no intrinsic limit to their lifetime. One AWO shows oscillations of speed and latitude with period ~128 d, excited when it passes oval BA. Small shorter-lived AWOs are also seen, lasting only 1-2 years. Sectors of SSTB between AWOs sometimes turn into white cyclonic circulations which can last for several years and progressively lengthen.

One AWO has probably persisted for at least 15 years in the S3 domain (~50ºS), and one for at least 26 years in the S4 domain (~60ºS). They show large variations in speed and latitude (following the ZWP), which often comprise oscillations with periods in the range ~33-50 d.

Chains of slow-moving dark spots are sometimes seen in the S2 and S3 domains, on or just south of the retrograde jet. They may be generated from persistent cyclonic turbulent sectors, as in the S.Temperate domain. The spotty sector in S3 lasted for 6 years.

Of the prograde jets, the S2 jet (36ºS) always carries several small dark spots, with a great range of speeds on the anticyclonic side of the peak; the peak speed is close to that observed from spacecraft. The S3 jet (43ºS), not previously detected from Earth, is recorded in every apparition from 2003 onwards. It has occasional dark spots, like those on the S2 jet, but uniquely, the S3 jet mainly carries white spots, on the cyclonic side of the jet. The S4 jet (53ºS) and S5 jet (61ºS) are not directly detected, but their presence is confirmed by rapid motions of spots on their flanks.

1. Introduction

Some of the circulations in Jupiter's atmosphere last for much longer than a single year, and many phenomena unfold over comparably long timescales. The intensive hi-res amateur imaging over the last decade has given a more detailed long-term database than ever before, so we can now look for long-lived features and long-term patterns even in high latitudes where historically little could be seen. Following on from our recent 12-year survey of the S. Temperate domain [Ref.1], we now present a similar view of the three high southern domains, from 36 to 61ºS, and beyond.

All observations up to 1991 were reviewed in 'The Giant Planet Jupiter' [Ref.2]. For the 1990s, we published full reports for each apparition in the Journal of the BAA (except 1993 and 1994 which were completed but not yet published), leading up to detailed multi-part reports for 2000/01 and 2001/02 [Ref.3] [see 'Publications' on this BAA web site: http://www.britastro.org/jupiter]. Since then, we have posted many interim reports [see 'Reports' on this BAA web site], but have not had time to post final reports except for a few apparitions (especially 2007 [Ref.4], q.v. for previous account of these far southern domains) and specific phenomena. However, the JUPOS project has compiled data and charts for all latitude bands since 1998, which form the basis of the present survey. This survey mainly covers 2001 to 2012, but extends back as far as 1986 and forward to 2013 for some analyses.

General background and a simplified domain nomenclature

The atmosphere of Jupiter is divided into dynamical units occupying fixed latitudinal bands or 'domains', separated by prograde (eastward) jets **(Fig.1)**. Each domain is divided by a retrograde (westward) jet. Within each domain the low-latitude half has cyclonic shear (a belt) and the high-latitude half has anticyclonic shear (a zone). The corresponding albedo pattern is routinely visible in the Tropical and Temperate domains. At higher latitudes, the dynamical patterns are not represented by visible belts and zones, and the retrograde jets are often weak and broad, so the custom of naming the jets after notional belts is less useful. Therefore, we propose the simpler and more realistic convention of labelling the domains and the prograde jets in order as S2, S3, S4... and N2, N3, N4..., as shown in **Fig.1** (also presented in Ref.5). The previous nomenclature for belts and zones can, of course, still be used as well.

The prograde jets which form the boundaries of the relevant domains are tabulated in **Table 1** [from Ref.5]. These high-latitude jets were unknown before the pattern was revealed by the Voyager flybys in 1979, and are still best characterised by spacecraft, but they have been detected in ground-based images in subsequent years as amateur imaging has improved. Spacecraft images track the smallest cloud features, yielding east-west wind speeds as a function of latitude which is called the zonal wind profile (ZWP). By contrast, ground-based images track distinct spots (weather systems), whose east-west drift rates may differ from the local wind speed; the relationship of these drift rates with latitude is called the zonal drift profile (ZDP) [Ref. 1]. The JUPOS analysis of hi-res amateur images presented here gives detailed ZDPs, which we compare with the spacecraft ZWP. In addition, by analysing pairs of hi-res images taken 10 or 20 hours apart with a new function in WinJUPOS, it is now possible to obtain a ZWP from the best amateur images [Ref.15]. Examples are shown in **Fig.2.**

The prograde jets at lower latitudes had been recorded intermittently by visual observations of dark spots. We now know that these drift at rates slightly slower than the peak jet speed, and on some jets at least, they are anticyclonic vortices 'rolling' along the edge of the jet peak [see

Appendix 2 in Ref.1]. However this is not necessarily true of the S1 (STBn) jet [Ref.1]. Now that we can detect spots moving along the S2 and S3 jets, in this report we will examine whether this paradigm also applies to them.

Within the best-observed domains on Jupiter, large features visible from Earth drift with a characteristic narrow range of speeds known as the slow current. Thus features in the S2 domain move with the S.S. Temperate Current (SSTC) with DL2 ~ -22 to -29 deg/mth, and overtake features in the S1 domain moving with the S. Temperate Current (STC) with DL2 ~ -11 to -17 deg/mth. However in higher-latitude domains, all features are smaller, and speeds of anticyclonic ovals are more variable; some undergo large oscillations in speed and latitude. In the highest-latitude domains, especially the S4 and N5 domains, the variations can be very large and there is no sign of a consistent slow current. As we will see, the ZDPs for distinct spots largely coincide with the ZWP.

Most domains show several classes of spots as follows [Ref. 2] **(Fig.3)**. Anticyclonic features are mostly oval circulations, often long-lived, viz. anticyclonic white ovals (AWOs), and in some cases red ovals which are the largest. Cyclonic 'closed' features are circulations, usually dark, nick-named 'barges'; but a few are white (cyclonic white ovals). Cyclonic 'open' features are regions of convective disturbance and turbulence, called rifted regions (large-scale) or folded filamentary regions (FFRs: small-scale). Cyclonic white ovals, barges, and FFRs, can interconvert. Dark barges (or smaller dark spots or longer belt segments) sometimes turn reddish just before they disappear, as though they "vanish in a puff of red smoke" [Refs.1 & 3].

The well-organised domains in the high southern latitudes all have long-lived anticyclonic ovals **(Fig.3)**. Domains S1, S2 and S3 also frequently have small spots in their prograding jetstreams. They also frequently have slow-moving dark spots close to their retrograding jets, although these positive DL2 drifts are modest and may be less than the full retrograding speed of the jets. (Likewise in the northern hemisphere, all these phenomena are frequently recorded in the N2 (N.N. Temperate) domain.)

This report is mainly a summary of JUPOS data over these 12 years, addressing the life histories and dynamics of spots, especially long-lived ones. Complete JUPOS charts for these domains since 2005 or earlier are provided in **Appendix 1.** Our analysis is not yet complete for every apparition, and there is scope for further analysis of shorter-lived spots and of the albedo (belt/zone) patterns. There is always a distinct albedo boundary at 53ºS, coinciding with the S4 jet, but otherwise, typical belt/zone patterns do not match the dynamical pattern in these high-latitude domains [Ref.2]. Further study is needed to find out whether there have been similar typical patterns in these recent years.

Figure 4 shows maps of the relevant latitudes, using one of the best available maps for each apparition. For image compilations of specific phenomena, the reader is referred to our on-line reports; but here we do show several image compilations from the 2003/04 apparition (in **Fig.7**), since some of these were not compiled at the time, those which were are no longer on our web site, and this apparition included several important phenomena in these domains.

2. Methods of observation and analysis

This report is based on the innumerable images taken by amateur observers around the world, whose names are posted on the JUPOS web site (http://jupos.org) or (http://jupos.privat.t-online.de/index.htm). Images are taken with a variety of telescopes, mostly with apertures 200-410 mm, using webcams to record hundreds of images within 1-2 minutes. They are processed with software which selects and aligns the best frames and excludes those taken in poorer seeing, most commonly Registax (http://www.astronomie.be/registax/). Further processing is done by each observer to enhance small-scale detail and contrast.

Measurements of 'spots' are done on-screen using the WinJUPOS program (created by G. Hahn), which is fully described and available at (http://grischa-hahn.homepage.t-online.de) or (http://jupos.org). In addition to the present authors, image measurements have been contributed in some years by Damian Peach and André Nikolai.

The frequency and quality of images has improved progressively over these 12 years, especially since 2003 when webcam imaging with selective image processing became widely adopted. Therefore the data in the later JUPOS charts are considerably more numerous and more accurate than in earlier years, and recently many very small features have been tracked.

In JUPOS charts of longitude vs time in this report, unless otherwise indicated, black points are dark spots, red points are bright spots, and < > indicate p. and f. ends of features.
Speeds are eastward or westward, expressed in degrees per 30 days (deg/mth) in System II longitude (DL2), or in m/s in System III longitude (u_3). 'Fast' and 'slow' are used in the eastward (prograde) sense, unless retrograde speed is specifically stated.
All latitudes are zenographic. South is up in all images.

Uncertainty in latitude is estimated from the scatter of measurements: for each spot, standard deviation is typically ± ~0.4º in the S2 domain, 0.5º in S3, and 0.6º in S4 (higher here because of foreshortening), and standard error of the mean is typically $\leq$0.2º because many measurements (usually >8) are averaged for each spot. Uncertainty in drift rate is conservatively estimated as 2 x 0.5º divided by track duration in months; nominal uncertainty for a 1-month track is thus 1.0º/month, but over longer intervals the precision is usually limited by real fluctuations in drift rate.

In the highest latitudes, the standard cylindrical projection maps (**Fig.4**) flatten the features excessively. Original images (**Appendix 4**) give better views. Resolution is also critical, so we show mainly images by Damian Peach, whose quality reveals high-latitude features that cannot be so well resolved on other ground-based images. The best maps for viewing these high latitudes are polar projections (**Fig.12**) or equirectangular projections (**Fig.3**: Cassini and HST maps). For the best Cassini maps see Ref.7.

3. The S2 jet (SSTBn jetstream)

This jet at 36ºS was never detected visually, and after its discovery by Voyager, it was first detected from Earth in 1988/89 [Ref.8], due to the innovation of fast hi-res photographic film in the 1980s, which revealed a few little dark spots moving with the jet. Several similar spots were tracked in 1989/90 and 1991/92. There were no further detections until 1999/2000/2001, when CCD imaging revealed several spots. Then from 2003 onwards, the advent of hi-res webcam imaging and intensive JUPOS analysis has allowed these 'S2 jet spots' to be detected in every apparition (see **Table 2**, and JUPOS chart in **Appendix 1(a)**).

These are always small dark spots, and are never very numerous. The data **(Table 2**, plotted in **Fig.5A)** show very diverse and variable speeds in the range from DL2 ~ -60 to -100 deg/mth, significantly slower than the jet peak in spacecraft data (**Table 1**). However, faster speeds have also been detected in the most recent apparitions, DL2 = -105 to -114, and these coincide in speed and latitude with the jet peak. ZDPs for the 2005, 2006, and 2011/12 apparitions, when there were plenty of spots **(Fig.5B,C),** show that the slower spots are all at slightly lower latitudes, i.e. on the anticyclonic side of the peak, closely following the ZWP.

Are these spots anticyclonic vortices, as on other jets? This paradigm is consistent with their ZDPs, and with their regular round shapes in the Cassini images (**Fig.3A**), even though the ground-based resolution is not sufficient to define their shapes.

How do these spots arise? They are not obviously related to the major features of the S2 domain; rather, they often seem to arise at specific locations in the adjacent S1 domain (STZ). In 2004 they were arising just p. oval BA. In 2006 and 2007, and again in 2011/12, they were mainly arising ~60-80º p. oval BA. In the sector from there to BA, the SSTBn edge was further N and/or disturbed. The nature of this constriction in the SSTBn/STZ was unclear, though it was notable in 2011/12, when it was marked by a curious disturbance ~60º p. BA which turned out to be the origin of new STB segment E ('STB Ghost'). It may be significant that in all the years when the S2 jet spots were arising p. oval BA, there was a dark turbulent STB segment f. BA (segment A), so this probably destabilised the S2 jet alongside BA. Indeed, the Cassini movie in 2000 [Ref.7] showed this process dramatically, with the turbulence from the STB dark segment streaming past BA to generate the dark spots on the S2 jet. In 2010, the S2 jet spots were arising p. STB segment D, perhaps in a similar way. But in 2005 the S2 jet spots were arising 60-70º p. the STB Remnant, a quiescent feature, in an undisturbed sector of STZ.

What happens to these S2 jet spots? They mostly disappear at or near the f. parts of STB structured segments: the STB Remnant (2004-2009), or segment A f. oval BA. We recorded ~10 spots which disappeared at or near the Sf. end of the STB Remnant, plus at least 7 which actually recirculated there, to become slow-moving in the STZ or retrograding in the STBs jet [Ref.1]. We also recorded ~14 S2 jet spots which disappeared near or alongside the dark-spotted region of STZ that comprises the Sf. 'tail' of the dark STB segment A, often decelerating and drifting north before they disappeared, plus 4 which actually recirculated into this spotty STZ. These may have been caught up in anticyclonic eddying associated with the dark spots of the Sf. tail. A few S2 jetstream spots also recirculated into undisturbed sectors of STZ, or just disappeared for no obvious reason.

Are there real variations in their abundance? There are never large numbers present. The record seems to show substantial variation in the number of the dark spots from year to year. But these spots are near the limit of resolution, so the records may be incomplete, e.g. if spots were sometimes inconspicuous against adjacent dark or bright or disturbed structures, or if measurers sometimes gave less attention to them. The recent detection of spots at the jet peak could be due to improved resolution. A more detailed review of the data could establish whether there are real variations in their number and appearance.

4. The S2 (S.S. Temperate) domain

The complete JUPOS chart for this domain from 2001 to 2012 is in **Appendix 1(b)**, and the AWOs are tracked on a compressed scale in **Fig.6**.
A previous report covering three years, 2004-2006, was posted [Ref.9]. The text of this and some other significant interim reports on our web site is reproduced in **Appendix 2.** An account of the AWOs has also been given by Morales-Juberías et al. [Ref.10]; their tracking agrees with ours.

4.1. Anticyclonic white ovals (AWOs) (40-41ºS)

It was the Pioneer and Voyager spacecraft which revealed the remarkable circulations in the S2 domain: small anticyclonic white ovals (AWOs) at 40-41ºS, often in chains alternating with cyclonic circulations at 38-39ºS, which may be white ovals, dark 'barges', or folded filamentary regions (FFRs). [Ref. 2, p.239]. In the Voyager maps there was a chain of 9 AWOs spaced 20-30º apart, alternating with cyclonic circulations, plus 3 AWOs scattered at other longitudes.

Although these AWOs were sometimes seen by visual observers, they were rarely tracked visually because of their small size. They were not routinely detected and tracked until the photographic film revolution in the mid-1980s, and even then they were usually described as tiny. Now, following the CCD and webcam revolutions, they are among the best-known features on the planet.

There have always been between 6 and 9 long-lived AWOs in this domain from 1986 to 2013, [**Note 1 in Appendix 3, & Fig.6**]. They have similar drift rates, and tend to form clusters, though when they approach close together (see below), they almost always drift apart again as though repelling each other. However, the 3 AWOs which disappeared probably all did so by merging with others (see below).

The mean latitude of the AWOs was 40.6 (±0.4) ºS from Earth-based photographs (1950-1991), and 40.5ºS from Voyager [Ref. 2, p.399]. We do not have an independent measurement of their latitude from JUPOS, as 40.5ºS has been adopted for these AWOs as a reference for checking the calibration of other measurements [**Note 2 in Appendix 3**]. The mean from Ref.10 was 40.9 (±0.2) ºS.

Whether the AWOs are always separated by cyclonic circulations is difficult to establish with certainty, because most cyclonic circulations were unresolvable from Earth until the last few years, but the best recent maps (**Fig.4**) show signs of cyclonic circulation between most pairs of AWOs <~30º apart, and they could be present in all cases.

History of the AWOs, 1986-2012:
To assess their long-term behaviour, we here summarise their history since 1986, when they were first systematically detected (**Fig.6**). We previously estimated [Ref.11] that from 1986 to 2001, four new AWOs appeared and five disappeared. Although some lasted only 1-2 years,

most of them lasted much longer. The improved observations and analysis since 2002 have allowed the tracking of smaller ovals than before, and confirm that ovals which last more than a year hardly ever disappear. From 2001 to 2012 (**Fig.6 & Table 3**), of the long-lived ovals, only two have disappeared, by the mergers in 2002, while four have appeared; it is also possible that a further one (A6) disappeared and was replaced the next year, although it could well have persisted as an invisibly small eddy which then re-grew [**Note 4 in Appendix 3**]. In the same period, six small AWOs appeared and lasted less than a year. (Some of these were white patches without dark rims, which may be less-well-defined circulations.)

It therefore seems plausible that the turnover in 1986-2001 was actually lower than originally estimated. More conservatively, if we assume that ovals A2 and A4 existed from 1986 and 1997 respectively despite being unrecorded in some years, there was only one disappearance (the first A8, by merger) and one appearance (A4), and one transient spot (in 1995; there might have been others too small to detect in these years).

In conclusion, over 27 years, only five stable AWOs have appeared, and three have definitely disappeared, probably all by mergers. So for stable AWOs, the average lifetime is nominally ~54 years [**Note 5 in Appendix 3**]; but in fact there does not seem to be any limit, since they have not been observed to grow old or dissipate, but only to disappear in occasional stochastic mergers. In contrast, transient AWOs also appear (seven recorded, but the recent frequency has been about one every two years), but do not last more than 1-2 years; and they can disappear either by merging, or by shrinking to invisibility.

Table 3:

Budget of AWOs:	Long-lived Appeared	Long-lived Disappeared	Possible extras	Transient (1-2 yr)
1986-2001	1 (A4)	1 (A8)	4 (A2 & A4)	1
2001-2002	1 (A8)	2 (A6 & A7)	--	--
2003-2012	3 (A0,A6,A7)	--	1 (A6)	6
1986-2012	**5**	**3**	**5**	**7**

The smaller AWOs sometimes appear within a long sector where there are no stable AWOs. They sometimes appear close to or possibly alongside oval BA (**Fig.6C**), as happened in 2004 March, 2004 Dec. (A0), 2006 Feb (A6 and a smaller one; **Fig.7D**), and 2010 May (A6a alongside oval BA and a smaller one just f. it -- just as the STB Remnant was disturbing this region). Two others, in 2007 and 2008, were not near BA. The minor AWOs have often disappeared on contacting, and probably merging with, major AWOs (with A1 in 2007, with A7 in 2008, with A6a and A7 in 2010) (e.g. **Fig.8**).

Convergences and mergers:

The long-lived ovals often have irregular spacings of ~30-50º, but tend to cluster together into chains with separations of 20-30º (**Fig.6**). Any approach to <20º (centre to centre) is not stable; although pairs often do approach to within 13-18º of each other, they always drift apart again, sometimes within days, always within months. However, whenever two have come within <12º of each other (with one exception: **Note 6 in Appendix 3**), they went on to merge, even though this did not happen until 1-2 months later.

In 1989-1991 there was an array of 5 AWOs, converging from ~30-50º apart until two of them, A7 and A8, were only 10º apart in 1992 Feb. They probably merged (unobserved) in 1992 March. (They were not alongside the large STZ ovals.) The two parent ovals had DL2 = -26.7 and -28.0 deg/mth, while the merged oval had DL2 = -31.0. This was probably a merger of two AWOs at the f. end of the chain just like that which occurred ten years later.

The merger of AWOs A6 and A7, in 2002 March, was well observed, and described in [Refs.3,10,11]. This occurred while these ovals were overtaking oval BA, and may have been triggered when this passage destabilised the close packing of the ovals. The merged oval probably merged with A5 in turn, a few months later during solar conjunction.

What might have caused these events? In view of the discovery that oval BA, in the S. Temperate domain, is accelerated when a dark turbulent STB sector is present f. it, we have to ask whether any similar feature in the SSTB could have pushed these AWOs together. However, we find no consistent pattern. In 1992, there was a large expanding white SSTB sector f. them [**Note 7 in Appendix 3**], which may well have pushed A8 towards merger (although many subsequent expanding white SSTB sectors have not had such an effect); but in 2002, the SSTB f. the converging AWOs was dark and not obviously turbulent.

S.S. Temperate Current:

These AWOs appear to constrain the speeds of all other major features in the domain: all types of cyclonic feature (dark spots, FFRs, and white oblongs) are generally trapped with respect to the AWOs and move at similar speeds. However there are interesting variations within these constraints, as described below. The mean speed of the SSTC in the visual era, up to 1991 varied only slightly as listed in **Table 4** below [Ref.2, p.238 – these speeds were from various features as the AWOs were rarely resolved].

Table 4: **Mean speed of SSTC** (deg/month)

		DL2	+/-SEM*
1887-1921		-25,3	1,5
1922-1946		-23,5	1,2
1949-1991		-25,9	2,0
1991/92 (A1-A3)		-26,2	0,7
1991/92 (A5-A7)		-28,8	1,6
1995-2001		-26,3	0,7
2003-2013		-28,5	

*SD of apparition means or (1991/92) of spot means

In 1991/92, the AWOs formed two chains which were converging; the rapid drift of the f. chain was unusual and was apparently augmented by the merger of A7-A8 at the f. end (speeds quoted above). From 1995 to 2001 they assembled into a single chain of 7 ovals with DL2 = -26.3, slightly faster than previous long-term averages. Then the last oval in the chain, A7, accelerated still further, and merged with A6 and probably with A5, and by 2003 the entire remaining chain of 5 ovals was moving at a rapid speed which has largely been maintained until the present, even as more AWOs have appeared. As can be seen from **Fig.6C**, plotted with a longitude system at DL2 = -28.5, this has been approximately the mean speed of the ovals from 2003 to 2012. The reason for this sustained rapid drift is still not known.

The variable drift rates of the AWOs correlate with latitude, as shown by our detailed analysis for 2006 and 2011/12 [G.A. & J.H.R., in preparation; see **Fig.18**], and for oval A0 (**Fig.9**). Although the ZDP for these ovals may be subject to selection effects [**Note 2 in Appendix 3**], it is close to the spacecraft ZWPs, but it is slightly below the ZDP for small dark spots in the SSTZ (blue points in Fig.18). This may indicate that these AWOs share, to a slight degree, the tendency of large anticyclonic ovals in other domains to follow a ZDP offset to low latitude [Ref.12].

An oscillating AWO:

Oval A0 has shown greater changes in drift rate than the other AWOs, probably because it is one of the smallest. Analysis of the JUPOS records shows that these are oscillations, with period ~103-147 days, induced when A0 passes oval BA **(Fig.6C & Fig.9)**. This was detectable in 2005, just after A0 had been born adjacent to oval BA, but was much more striking in 2007, and occurred again at subsequent passages in 2009 and possibly 2010/11. Each time, the oscillations started with a sudden deceleration such that A0 remained close to BA for some time, before starting to oscillate. However the oscillations were a zig-zag rather than a sine wave, with abrupt changes of speed taking only a few days in 2007, stretching to 1-2 weeks in later years. The mean period in 2007-2008 was ~128 days but the data suggest that the period may have shortened as the amplitude decayed with time after each passing of BA. A0 simultaneously oscillated in latitude, correlated with its speed, showing a ZDP which intersects the Cassini ZWP (**Fig.9B**). This behaviour is striking but has not been recorded for other AWOs, probably because most of them are larger and more constrained in the chain, while smaller ones are too affected by random variations to be useful for analysis.

Discussion:

It is notable that the number of the AWOs has remained between 6 and 9 throughout the 27 years reviewed, suggesting that the number is somehow regulated. (Subsequently, in late 2013, another has appeared bringing the total to 10, though it is very small.) The maximum number may be ~12, as was observed by Voyager, but that might have been an unusual time [Ref.2, p.238-243]. The number of cyclonic circulations may be similarly regulated although they are more difficult to count. When the number of AWOs drops below 6, new ones develop from unresolved small eddies to replace those lost.

The same phenomenon is known in the S. Temperate domain, where there are always 2-4 large AWOs or other structured segments [Ref.1 & Ref.2, p.264-5], and new ones develop to replace those that have merged.

One hypothesis is that these features are controlled by a planetary-scale wave in each domain. However, no such wave is directly observed, and the ovals do not have a uniform spacing as one might expect from a wave. Although the S2 AWOs are mostly grouped into clusters with a spacing of 20-30º, this seems to be a minimum stable spacing, and never extends all round the planet; there is a continuous range of larger spacings so one cannot define a characteristic wave-number. Another (not incompatible) hypothesis is that these ovals develop to take up surplus energy and vorticity that cannot be accomodated in the jets [Ref.2, p.264-5], so a certain number of them may be required for this function, regardless of their spacing.

Oval BA has a variety of influences on the AWOs. The smallest AWOs tend to appear next to oval BA. Oval A0 was regularly induced to oscillate on passing BA. The drift rates of other AWOs may also be affected on passing BA though not so systematically. And the merger of two major AWOs in 2002 occurred just as they were approaching BA. Likewise, the GRS has had various influences on white ovals in the S.Temp. domain [Ref.2, pp.226 & 229, & Ref.11], although there are no exact parallels.

4.2. Cyclonic white ovals and oblongs (38-39ºS)

Where the space between two AWOs is short, it is common for the SSTB there to turn into a white oval or oblong (elongated white sector), at 38-39ºS. Their form and latitude imply that these are closed cyclonic circulations. They never develop simultaneously in adjacent sectors. Their lifetimes range from several months to nearly 6 years. They always expand progressively during their lifetime. In all these properties they resemble the 'STB Fade' sectors that occurred in the STB in earlier decades, which were shown by Voyager to be closed cyclonic circulations.

The eight instances during 2001-2012 are listed in **Table 5**, named according to the pairs of AWOs which bounded them.

The expansion rates for each of these white oblongs are shown in **Fig.10**. The expansion rate at a given time depends on the length, but not linearly; instead there appear to be two thresholds above which the expansion accelerates. Expansion is barely perceptible when the oblong is an oval <10 deg long, but once it is longer, it lengthens faster, often at a fairly steady rate which has ranged from 0.3 to 1.4 deg/mth, although with some fluctuations. In three cases when the length exceeded 20-26º, the expansion suddenly proceeded even faster (1.9 and 2.6 deg/mth in two cases, too short-lived to measure in the third). These rates are very similar to those measured for 'STB Fade' sectors, which expanded at 0.7 to 1.9 deg/mth with two faster instances [Ref.2, p.229].

Similar white oblongs have been recorded in previous years, sometimes being much longer, e.g:
--One was ~34º long in the Voyager 1 map in 1979, noted to be a white sector with a wavy closed border resembling the 'STB Fade' [Ref.2, p. 239].
--One existed between ovals A3 and A5 in 1986-1989, when the two ovals were rapidly diverging, until it was just over 100º long.
--Another existed between ovals A8 and A1 in 1991-1995, rapidly expanding and apparently pushing A8 to merge with A7, and also reaching just over 100º long [**Note 7 in Appendix 3**].

It is likely that the expansion is intrinsic to the cyclonic circulation, as the white oblong sometimes forms before the expansion begins, and one example in (2006) was not bounded by AWOs. The alternative, that divergent motion of two AWOs induces a cyclonic white oblong between them, could not account for these examples.

Where the space between major AWOs is long, different phenomena are seen, without such special organisation. Tiny AWOs occasionally appear and are short-lived, as described above. Cyclonic white ovals also occasionally appear and persist for a year or more, but do not develop into expanding lozenges. Small dark spots or streaks are also seen, always moving more slowly than the AWOs, as discussed below.

4.3. Cyclonic dark spots turning red and fading

A recently recognised phenomenon is that dark cyclonic belt segments or barges in several domains sometimes become reddish just before fading away [Ref.3, p.215]. Three examples were recorded in the S.S.Temp. domain.
-- In 2003/04: a small, very dark brown streak in Dec-Jan. had become very red by Feb.10, was turning white by Feb.27, and quickly reappeared as a white cyclonic oval, which persisted till 2004 July, and probably till 2006 after AWO A0 formed just p. it. It is shown in **Fig.7A**.
-- In 2007 (Feb-Mar.). [unpublished data].

-- In 2008 July. [Ref.13, see Appendix 2]. It was a short dark bar between oval A6 and a cyclonic white oval. In early July, the cyclonic oval broke up suddenly, just as it was passing oval BA. At the same time, the dark bar became brown then faded away, leaving reddish-brown haze which drifted p. to surround A6 in late July.

4.4. Slow-moving dark spots in the S2 domain (~40ºS)

Sometimes, the JUPOS chart reveals a sector containing slow-moving dark spots at ~40ºS. These usually have DL2 ~ -21 deg/mth, sometimes as slow as -12 deg/mth, so they are slow relative to the AWOs which dominate this domain, but never retrograding. They can be seen in the charts [Appendix 1(b)], mainly in specific sectors, and on some of the maps in **Fig.4**.
--In 2005 and 2006, they were present for ~40º p. AWO A8, with DL2 = -21, on an apparently undisturbed sector of SSTB.
--In 2009, short-lived dark spots were present in the sector f. small AWO A6 until this AWO disappeared along with the white oblong p. it; then they were present in that sector instead, f. AWO A5. There was a turbulent cyclonic region (FFR) p. A5.
--In 2010/11 and 2011/12, they were present f. AWO A2; this sector of SSTB was otherwise quiet, but there was a FFR p. A2.

Table 6: Slow-moving dark spots in S2 domain
from our full analysis of two apparitions [GA & JHR, in preparation]:

Year	DL2 (±SD)	Lat. (±SD)	n
2006	-21.0 (±2.6)	-40.6 (±0.3)	11
2011/12	-15.7 (±3.7)	-40.0 (±1.0)	4

It is unclear how these spots are generated, since they are not consistently associated with any other type of feature. From their latitude, they are on the anticyclonic side of the retrograde jet (in the nominal SSTZ), so they may be comparable to the slow-moving dark spots seen in the STZ f. dark STB sectors [Ref.1]. We therefore suspect that they may be similarly generated f. cyclonic regions with small-scale turbulence in the SSTB; for example, the FFRs which were visible in late 2009 and in 2010-2012. No such FFRs were detected in 2005-2006 and in early 2009, but it is possible that even smaller turbulent regions were responsible, below the resolution of images. This would be consistent with the Cassini movie, which shows a sector of slow-moving SSTZ dark spots tens of degrees p. the GRS, with a small turbulent focus in the SSTB at their p.end, which may well have been generating the slow-moving spots.

5. The S3 jet (S^3TBn jetstream)

This prograde jet at 43ºS was not detected from Earth until 2003 March-April, when a few fast-moving spots were identified in the JUPOS chart. The jet has been recorded in every apparition since [see JUPOS chart in **Appendix 1(c)**]. The earlier non-detection was likely due to insufficient resolution before the webcam era; but there may also have been a real change.

In the Cassini map and movie made in 2000, no such spots were present (**Fig.3A**). Around almost half the circumference, the S3 jet latitude comprised a narrow dark belt ['(S)SSTB': Ref.2], and around the remainder, the S3 domain was mostly occupied by large, almost-continuous FFRs, without distinct spots on the jet.

Uniquely, this jet carries white spots as well as, or sometimes instead of, dark spots. The records are fully listed in **Table 7** and **Fig.11A**, and can be summarised as follows.

Numerous jet spots were tracked in the 2004, 2005, and 2006 apparitions, with white and dark spots in largely separate sectors; but only small numbers, almost all white spots, were tracked in each year from 2007 to 2010. Then there were large numbers again in 2011/12, mainly white spots [**Fig.4 & Appendix 4(C)**]. Looking at the best maps from these years, it seems that these variations are probably real, as the white spots could be seen easily in some years, esp. 2011/12 (**Fig.4** – light blue arrows), and they seem to be genuinely rare in the hi-res maps from 2007 to 2010, as in the Cassini map. However, given the still-limited resolution, it is possible that spots were sometimes missed if they were inconspicuous against adjacent dark or bright or disturbed structures.

This jet is unique, not only in producing white spots, but also in that they are on the cyclonic side of the jet peak as defined by spacecraft. This is confirmed by ZDPs from JUPOS data (**Fig.11B**,**C**). The white spots are S of the jet peak, on a cyclonic gradient coincident with the ZWP, while the dark spots are at the peak or on the anticyclonic side. The dark spots could thus be anticyclonic vortices, consistent with the paradigm for other jets [see Background, above], although they could just be small spots which drift with the ZWP. However, the white spots must be different in nature.

How do these spots arise? The image quality was insufficient to resolve the source regions in 2004 and 2005, but better images in 2006 showed small-scale streaks and mottling in the active sector. In 2011, the white spots were emerging along the N edge of a narrow sinuous segment of dark S^3TB [**Appendix 4(C)**]. These structures were suggestive of unresolved turbulence, and the Cassini images showed clearly that there can be turbulent sectors in this domain which appear bland in ground-based images. Perhaps it is extensive FFRs such as these which produce S3 jet spots in some years.

6. The S3 domain

Fig.12 shows polar projection maps of these regions, which show the higher latitudes with less distortion. We earlier posted a polar projection map from 2007 May, along with the Cassini map, in our final report for 2007 (Ref.4: Fig.3 therein). We also posted a set of maps from 2009 August showing the expansion of the 'Bird Strike' impact cloud [Ref.14].

6.1. 'S.S.S. Temperate Belt' latitudes (S^3TB, 45-48 ºS): the S.S.S. Temperate Current (S^3TC)

Although few features have historically been tracked in this domain, those that have support the existence of a steady 'slow current', as in lower-latitude domains, named the S^3TC, with mean DL2 = -8.3 (±5.7) deg/mth [Ref.2, pp.238-240; the values are reproduced in **Table 8**]. (The features tracked were all dark spots or streaks, except for a few white spots tracked by the New Mexico State University Observatory.) This is almost stationary in System III (DL3 = -0.3 deg/mth), but this is likely to be merely a coincidence, since no other domain on the planet has exactly this slow current speed.

Do the recent hi-res data support the existence of the S^3TC? The JUPOS charts (**Appendix 1(d)**) show no long-lived features, but several dark spots or streaks can be tracked in each apparition. Most are short-lived though a few dark streaks last for several months. They are at latitude 47-48ºS. They have DL2 ~ -8 to -11 deg/mth, confirming the historical S^3TC. Taking only dark streaks at >46.5ºS which lasted for more than a month, the mean DL2 is -9.9 deg/mth, lat.47.0ºS (**Table 8**). There are also rarer features at ~46ºS which drift much faster. However, if shorter-lived streaks and smaller spots with well-defined tracks are also included, from 46 to 48ºS there is a continuous range of DL2, with a well-defined ZDP, slightly shallower than the Cassini ZWP **(Fig.13A)**.

As will be shown below, the S^3TC does not seem to apply to the AWOs in the 'S^3TZ' at ~50ºS, which have a much greater range of speeds. However the S^3TC did apply to a long-lived sector at 49ºS containing small retrograding dark spots (see below), and to the cores of the Comet SL9 impact sites in 1994 (see **Appendix 3**).

6.2. Slow-moving dark spots in the S3 domain (~49ºS)

The JUPOS charts (**Appendix 1(e)**) also show many slow-moving (slightly retrograding) dark spots or streaks at ~49ºS, close to the retrograding jet. Remarkably, for 6 years most of these occurred in one persistent sector which moved with a different speed, matching the S^3TC or System III, at L3 ~150-220 (2005-07) --> 180-250 (2009-10). This sector survived despite the long-lived AWO crossing it twice. On the maps (**Fig.4**), this sector seems to be a string of narrow dark spots or streaks like the Sf. extensions of dark STB segments (see below), and like them it is sometimes visibly oblique, suggesting that these spots originate from a persistent disturbance at the Np. end of the sector. However, the nature of this disturbance is not obvious.

These spots are at ~49ºS, i.e. in the anticyclonic domain S of the retrograding jet at 48ºS according to Cassini data, but on the jet according to Voyager data (**Table 8**). Their ZDP is shown in **Fig.13B**; it shows an unusual degree of scatter. This may be due to the fact that almost half of the spots drifted southward during their lifetimes, typically by ~1º latitude, in spite of maintaining a constant drift rate (the best-documented example is shown in **Fig.13C**). These spots may be drifting along the oblique line of the chain while maintaining a constant drift rate, suggesting that the ZWP varies from one end of the chain to the other. Alternatively, they may actually straddle the peak of the retrograding jet, which has almost identical drift rate and latitude in the Voyager and New Horizons data (see **Table 8,** & section below).

This sector strongly resembles the 'Sf. tail' of the dark STB segment f. oval BA [Ref.1], in the S1 domain. This tail consists of slow-moving dark spots in the anticyclonic STZ, which tend to drift southwards during their lives (although they do tend to change their speeds in accordance with the ZWP, except for those which cross the latitude of the retrograding STBs jet), and their ZDP has varied from year to year. By analogy with this sector in the S1 domain, we therefore suspect that the sector of dark spots in the S3 domain lay Sf. a long-lived turbulent cyclonic sector – possibly an extensive but low-contrast FFR, like those shown in the Cassini map, which are unresolvable in ground-based images. Continuous generation of these spots from a cyclonic FFR would explain how the sector was able to survive passages of the long-lived S3-AWO-1 through it. Consistent with this hypothesis, the HST map in 2008 May **(Fig.3B)** indeed showed a large FFR in the S3 domain p. the dark spots sector.

In contrast, a ZDP of the dark spots at this latitude in 2011/12 (when they were not restricted to a specific sector) showed a good anticyclonic gradient coinciding with the Cassini ZWP **(Fig.13A).**

6.3. Retrograde jet (48-49ºS)

The S3 domain has a retrograde jet at 48-49ºS. In all spacecraft ZWPs, like most other high-latitude retrograde jets, it has a broad peak with modest retrograding speed, ranging from DL2 ~

+9 to +33 deg/mth (u3 ~ -6 to -14 m/s; **see Table 8**). The peak latitude has varied considerably between spacecraft data sets. It was highest in the data from Voyager, which appears to reflect a global systematic difference between data sets, but may also reflect real variations, as our data on dark spots at 49ºS (above, & see **Table 8**) match the Voyager jet peak in the 2005-2010 long-lived sector, but match the Cassini anticyclonic profile in the 2011/12 apparition.

Possible variation in this retrograde jet is also implied by ZWPs from amateur images (**Fig.2**). Although in the ZWPs in 2012 Sep. & Nov., this jet had a profile similar to the spacecraft mean and the New Horizons ZWP (u3 ~ -10 m/s, DL2 ~ +22 deg/mth), it was more sharply peaked in the ZWP of 2012 Dec. (u3 ~ -20 m/s, DL2 ~ +51 deg/mth); and even more so in 2010 Sep. (reaching u3 ~ -38 m/s, DL2 ~ +105 deg/mth). By comparison, other jets in these high latitudes showed much better agreement with spacecraft values. Again, this suggests that there may be real variations in the ZWP in this domain.

6.4. Long-lived AWO (~50ºS)

At ~50ºS there are always one or two AWOs, which are always white. Of those present in 2012, one which we call oval 1 or S3-AWO-1 has been definitely tracked since 2006, and probably since 1998. The connections between solar conjunctions are less certain in those earlier years because the observations were sparser, and this oval shows frequent large variations in drift rate; but as it has always persisted through each apparition, and the implied mean drifts between apparitions are always within its typical drift range, it is very likely to be a single AWO that has persisted at least since 1998. In some apparitions there is a second AWO, which is shorter-lived, although there may have been a single one persisting from 2004 to 2007. The tracking of these AWOs is shown in **Fig.14** and **Appendix 1(e)**, and the ZDP in **Fig.15**. Images showing oval 1 are in **Fig.7D and Appendix 4**.

The long-lived oval 1 shows the same dynamical properties as the oval at ~60ºS (below) and the ovals in the NNTZ [Ref.12]: its speed is highly variable, and often oscillates, and follows a gradient in general agreement with the zonal wind profile. The shorter-lived ovals show the same properties. More specifically:

--The speed of these ovals is highly variable, ranging from DL2 = +4 to –54 deg/mth for oval 1, and up to -56 for a short-lived oval in 2007 [see note below] **(Fig.15A)**. Although speeds occur throughout this range, they are bimodally distributed, clustering around +2 and -25.
--Often the motion is oscillating, with speeds within the above range, and period in the range from 24 to 60 days. The mean period is 40.6 days for oval 1 (over 13 cycles), and 38 days for shorter-lived ovals (over 4 cycles) **(Fig.15B)**, but the most sustained periods were ~33 days (in 2002/03 and 2006, 4.5 continuous cycles each time).
--To study these oscillations further, we selected 9 track segments (from 8 apparitions) in which one or more cycles were observed with well-defined cycle lengths up to 43 days, and calculated the average for period (in days), amplitude (in degrees of longitude), latitude (from 50.1 to 50.8ºS), and speed (DL2), over each track segment. The results show significant correlations of period with amplitude **(Fig.15C)** (R^2 = 0.48) and with mean latitude (data not shown; R^2 = 0.56). Thus longer cycles tend to have larger amplitudes, as might be expected, and lower mean latitude (though not lower mean speed; data not shown). The physical significance of these correlations remains uncertain.
--Occasionally oval 1 has longer runs, maintaining fairly constant speed for 60-70 days. These runs can also be at any speed, ranging from -53.6 deg/mth in 2007 to +0.4 deg/mth in 2011/12

[see note below]. No cause for these long runs can be discerned; they do not occur in any systematic relation to the sector of slow-moving dark spots.
--The ovals obey a strict latitude-vs-speed relation (ZDP) **(Fig.15A)**, which is the same for oval 1 and the shorter-lived ovals, and agrees with the anticyclonic ZWP, except that the ZDP throughout most of the speed range is slightly further south.
--Changes in drift and latitude occur simultaneously, within the minimum measuring interval which is several days. There is no perceptible lag between them.
--Notes on remarkable speed changes:
--*In 2007*, oval 1 and another AWO ~100º p. it were both weakly oscillating in near-synchrony, and then both rapidly accelerated to exceptionally fast and sustained speeds of DL2 = -53.6 (oval 1) and -56 (the other oval).
--*In 2011*, oval 1 suddenly changed its drift rate from DL2 ~ -33 (throughout Sep.) to +3 (throughout Oct.) within a few days; at the same time the latitude changed from 50.5 to 49.5ºS. This change has been studied in detail by Schmude [Ref.17], whose measurements are close to ours. The shift occurred just as oval 1 was about to collide with a retrograding dark spot at 49.2ºS with DL2 = +7; they were just 8º apart when oval 1 changed course, then the dark spot disappeared (**Appendix 1(e)**). It seems surprising that such a small spot would so powerfully affect the long-lived AWO, but it is possible that this dark spot was just the leading element in a sector of retrograding features, perhaps with altered ZWP.

7. The S4 jet (53ºS)

This prograde jet at 53ºS is well defined in spacecraft ZWPs, and coincides with a fixed albedo boundary which marks the edge of the dark South Polar Region [Ref.2]. However, no spots have ever been recorded moving with its full speed. The rapid speed of its northern flank is displayed by the S3 AWOs described above, with speeds ranging up to -56 deg/mth at 51ºS.

On its peak or southern flank, rapid speeds were revealed at 54ºS by the impact clouds of 1994 and 2009 [see **Appendix 5**]: southerly patches of the 1994 SL9 impact clouds, with DL2 up to -36 deg/mth, and a northerly patch from the 2009 impact cloud, DL2 = -48. However, these clouds were at high altitude, so they were probably affected either by the thermal decline of tropospheric wind speeds with increasing altitude, or by a specific stratospheric prograding current. These speeds were much less than the full speed of the S4 jet.

Notable waves were imaged on the albedo boundary at 53ºS after the 2009 impact [Ref.14 & **Appendix 5**], and the fact that they were prominent in UV images from HST (along the border of the south polar haze) [Ref.18] makes it more likely that they were indeed undulations of the S4 jet. We have not noticed such prominent waves on this boundary at other times (see **Fig.3**) although a group can be seen on the maps from 2008 May (**Fig.3B & 4**), and a systematic search remains to be done. Further inspection of the 2009 amateur images suggests that the waves were prograding with a modest speed, much less than the rapid speed of the jet, and they gradually subsided after 2009 Aug.21. Curiously, the set of images from 2009 Sep. **[Appendix 4]** shows similar waves, also modestly prograding, but they were in a different longitude range, too far away to have spread along the jet from the impact; they developed on Sep.1 in that location. It is therefore possible that these were occasional waves unrelated to the impact.

8. The S4 domain

Rare spots and streaks

These latitudes from 53-61ºS are traditionally considered to be within the South Polar region, but can now be recognised as another domain (the S4 domain), bounded by prograding jets, as spacecraft have revealed the pattern of alternating jets continuing to even higher latitudes. Few features are observed here, and they are mostly small and short-lived with rather diverse drift rates, but there is at least one long-lived bright anticyclonic oval near 60ºS (see below).

Apart from this AWO, the JUPOS charts revealed only 35 probable tracks in this domain from 2002 to 2013, only 17 of which were secure enough for analysis. They fell into two groups **(Fig.18)**. Most were dark streaks between 54-55ºS, with prograding drifts in the range DL2 = -12 to -32. The others were at 57ºS: three small dark spots DL2 = +5 to +6, and one white spot accelerating from +18 to +11 in its 7-week existence. These coincide with the velocity minimum in the Cassini ZWP. These small features are close to the spacecraft ZWP and do not reveal any distinct slow current for the S4 domain.

Long-lived AWO(s) (~60ºS)

At least one bright oval is routinely tracked near 60ºS in every apparition. From its latitude, it must be anticyclonic. Up to 2008, a single bright oval was tracked, as described [Refs.4 & 12]. The description from Ref.12 is reproduced here:

A similar oval in the South Polar Region

Since 1994 there has always been at least one bright oval at ~58-60ºS, 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. 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). Indeed, Morales-Juberias et al.[Ref.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 [Refs.22,23].

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 x 3200 km: Ref.15)
--It shows large and sudden changes in drift rate, ranging from DL2 = +5 to –46 deg/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 42-66 d.)
--It drifts faster when at higher latitude (Refs.9&14). There is no perceptible lag between changes in drift and latitude. The graph 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 ºS), though never strongly coloured.
-- It is methane-bright, as shown in HST images in 1994, 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).

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The JUPOS chart from Ref.12 is now brought up to date [**Appendix 1(g) & Fig.16**]. Since 2006, the long-lived bright oval here (here labelled A) has been joined by one or more others, and with their frequent wild variations in drift rate, and occasional mergers, it has not been possible to keep track of them reliably through solar conjunctions. From 2006-2008, both the long-lived oval (A) and a second one with regularly oscillating track (B) persisted, but in 2009 only one of them remained; they may have merged during solar conjunction. More ovals appeared (or, were identified in improved images), so in 2011/12 there were four of them. Nevertheless, in each apparition from 2009 to 2012/13 there has always been one oval larger than the others, and it is possible that this is still oval A [**Appendix 1(g) & Fig.16**]. The implied drifts during solar conjunctions are within the range of variation that oval A has shown previously. Usually this large oval has appeared slightly reddish **[Fig.3 & images in Appendix 4]**. Other ovals tracked in this latitude were smaller, although some of them were clearly shown on hi-res images as they were bright white.

Both the long-lived oval A, and shorter-lived ones, have very variable speeds, ranging from DL2 = +7 to -47 deg/mth. The distribution of drift rates has a single peak at DL2 ~ 0, but also has a long 'tail' to high prograding speeds **(Fig.17B).** Sometimes the variations in speed are abrupt and irregular, but often they comprise oscillations, with several cycles observed per apparition. Oval B oscillated with period 33-54 days throughout 2006-2009, and since then most of the tracks have continued to show oscillations, with periods of ~36-80 days. Periods around 50 days appear to be most common.

All these speed changes are linked to changes of latitude: the ZDP follows an anticyclonic gradient which agrees well with the Cassini ZWP at the northern and southern limits, but has a significantly different profile in between (**Fig.17A**). This ZDP is very consistent between different years and different spots. In other domains, notably the N.N. Temperate domain, larger anticyclonic ovals follow ZDPs at slightly lower latitude than smaller ovals [Refs.1 & 12], and this tendency can also be seen in this domain for oval A (and the larger oval in recent years), but only in the mid-range of speeds (DL2 ~ -4 to -20 deg/mth). At faster and slower speeds, this large oval occupies the same latitude range as smaller ovals.

Some of the best recent images showing this and other long-lived ovals are shown in **Appendix 4**, as well as some methane-band images showing that it is still methane-bright.

9. The S5 jet (61ºS) and further south

Within the dark and largely featureless South Polar region, HST and Cassini images have confirmed the existence of a prograde jet at 61ºS (S5 jet) (**Table 1**), close to a rather irregular albedo boundary at ~62-63ºS which is the edge of an even darker South Polar Belt. These spacecraft also discovered another prograde jet at ~67ºS (S6 jet).

Although no spot has been tracked with the peak speed of the S5 jet, we have tracked rapidly-prograding white spots less than 1º N of it (the S4-AWOs described above) and S of it (at 62ºS in 2010).

> In 2010, we tracked a white spot which appeared to be emitted by a white oval at 60ºS on 2010 Aug.18, crossing the latitude of the S5 jet [**Fig.12B & Appendix 1(g)**]. From Aug.18 to Sep.18 it had mean latitude 62.1 (+/- 0.7, s.d.) ºS with DL2 = -28 deg/mth; then it shifted back closer to the jet peak and from Sep 21 to Oct 27 was at latitude 61.8 (+/- 0.5) ºS with DL2 = -64 deg/mth.

We have also tracked one other spot in the S5 domain, also rapidly prograding (shown in **Appendix 4,** images in 2007 May-June). As noted in [Ref.4]:

> "In 2007, we tracked a spot further south than any previously: a distinct white spot at 65ºS (in the south edge of the S. Polar Belt), with remarkably fast speed: DL2 = -87 deg/mth. This fits exactly onto the Cassini ZWP within an anticyclonic zone that could be named the 'S5TZ'." (This was evidently influenced by the S6 prograde jet at ~67ºS.).

10. Conclusions

We have presented an overview of the S2, S3, and S4 domains in the high southern latitudes of Jupiter, from 36 to 61ºS. A compilation of ZDPs over the whole range is shown in **Fig.18,** with the Cassini ZWP for comparison. In the S3 and S4 domains, the ZDPs for major ovals and small dark spots do not deviate from the ZWP as much as they do in lower-latitude domains. The form of the deviation is the same for all three domains.

The most conspicuous and long-lived features of these three domains are **anticyclonic white ovals (AWOs)**. Three or four have been tracked for 27 years in the S2 domain (40.5ºS); one probably for 15 years in the S3 domain (~50ºS) and one probably for 26 years in the S4 domain (~60ºS). All of these may have existed for much longer, before modern imaging could detect them. In the S2 domain, from 1986 to 2012, there were always 6-9 long-lived AWOs, among which three disappeared (probably all by mergers) and five appeared; the nominal mean lifetime is ~50-60 years but this may be limited only by occasional, stochastic mergers. Small shorter-lived AWOs are also seen, lasting only 1-2 years. One small S2 AWO shows oscillations of speed and latitude with period ~128 d, excited when it passes oval BA. Whereas the AWOs in the S2 domain mostly show little variation in speed, those in S3 and S4 show large variations in speed and simultaneously in latitude, which often comprise oscillations with periods mostly in the range ~33-50 d.

Cyclonic features are conspicuous only in the S2 domain, where short SSTB sectors sometimes turn into white oblongs, which can last up to 5.6 years. These are probably closed circulations, and always expand at rates which depend on their length. Other cyclonic features are folded filamentary regions (FFRs), and dark streaks or 'mini-barges', which sometimes turn red before they disappear.

Chains of slow-moving dark spots are sometimes seen in the S2 and S3 domains, as in the S1 (S.Temperate) domain; they may straddle the **retrograde jet**, or lie on its anticyclonic flank, depending on the local ZWP. Although these spots are often most noticeable f. AWOs, our results suggest that they are actually generated from persistent cyclonic turbulent sectors, which in S1 and S2 are trapped against AWOs: viz. a dark STB segment in S1, a large FFR in S2, and hypothetically a long-lived FFR in S3. The spotty sector in S3 lasted for 6 years and showed evidence for an alteration of the canonical ZWP.

The prograde jets differ in their characteristics. The S2 jet (36ºS) carries small dark spots in every apparition, although their number appears to vary. In recent years their maximum speed averages DL2 = -110 deg/mth at 36ºS, close to the average peak from spacecraft ZWPs. The spots show a great range of speeds, with a ZDP showing that they are on the anticyclonic side of the jet peak, consistent with the lower-latitude paradigm of dark jet spots as anticyclonic vortices rolling along the flank of the peak. The S3 jet (43ºS), not previously detected from Earth, is recorded in every apparition from 2003 onwards in our data. Dark jet spots, which are infrequent, have a peak speed of DL2 = -101 deg/mth at 43.0ºS, with others following an anticyclonic ZDP, as for the S2 jet. Uniquely, though, the S3 jet mainly carries white spots, with the same speed but at ~43.7ºS, on the south side of the jet, with a cyclonic ZDP. They apparently arise from specific sectors in the S3 domain which may represent unresolved disturbances. The S4 jet (53ºS) does not carry detectable spots, but its presence is confirmed by rapid motions of the S3 AWOs on its N flank and rare impact-generated clouds on its S flank. The S5 jet (61ºS) is also not directly detected, but rapidly-prograding white spots have been recorded on its flanks.

Each domain does have its particular characteristics. The S2 domain is dominated by numerous AWOs, often forming regular chains separated by cyclonic regions which may be FFRs or white oblongs or dark mini-barges. The S3 domain has only one long-lived AWO, and spacecraft images reveal very extensive cyclonic FFRs which are unresolvable from Earth. The S4 domain is largely featureless but has one long-lived AWO. Thus, although these higher-latitude domains are more difficult to observe and contain smaller features, they show phenomena comparable to those of lower-latitude domains, and some remarkable features of their own.

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FIGURE LEGENDS

Figure 1. Diagram of Jupiter's belts, zones, and jets, with (at left) our proposed new nomenclature for the domains. (Temp., Temperate; Trop., Tropical; other abbreviations as previously).

Figure 2. Zonal wind profiles from amateur images, by map correlation in WinJUPOS (analysis by Grischa Hahn: Ref.15).
(A) 2010 Sep.4; compared with ZWP from Cassini.
(B) 2012 Sep.-Dec; compared with ZWP from New Horizons.
(All credits and references are on the figure.)

Figure 3. Hi-res maps from spacecraft showing the major features of the four domains. These maps use equirectangular projection which does not distort high-latitude features excessively.
(A) Map from Cassini (2000 Dec.11-12: credit NASA/JPL/University of Arizona). About 270º of longitude are shown; see **Fig.4** for a full-length version. Latitudes of the prograde jets are indicated. Typical major features are indicated in each domain. AWO, anticyclonic white oval; FFR, folded filamentary region (cyclonic). Oblique red arrows indicate S2 jet spots on SSTBn.
(B) Map from HST (2008 May 9-10; credit NASA/ESA/STScI/UC Berkeley, M.H. Wong & I. de Pater) [Ref.16]. About 270º of longitude are shown. See **Fig.4** for a full-length map from amateur images taken at the same time.

Figure 4. Maps in each apparition. One of the best available maps for each apparition is shown, from mid-SEB to the south pole, with the high-latitude features labelled.
All maps use cylindrical projection and System II longitude (L2), and were made using WinJUPOS, except the Cassini map which uses equirectangular projection (reduced copy from Ref.7). These are the same maps used in our long-term S.Temperate report [Ref.1] All the long-lived AWOs are labelled on each map, those in the S4 and S3 domains by black arrows, and those in the S2 domain by cyan labels above the map. Oblique arrows on some maps indicate examples of jetstream spots: red for dark S2 jet spots, dark blue for dark S3 jet spots, light blue for white S3 jet spots.

Figure 5. The S2 prograde jet.
(A) Records of observed speeds, 1988-2012.
(B,C) ZDPs in 2005 and 2006 and 2011/12 (analysis by G.Adamoli, from draft JUPOS/BAA reports). A red cross marks the average peak of the jet from spacecraft.

Figure 6. Longitude-vs-time charts for the S.S.Temperate (S2) domain, especially the long-lived AWOs. Longitude is plotted as L2 – 0.9 or 0.95 deg/day. These are compact charts; see **Appendix 1(b)** for full-size JUPOS charts from 2001 onwards. In all charts, ticks on the vertical axis denote the start of each calendar year.

(A) Diagram indicating the tracking of the AWOs from 1989-2001. Coloured points are the L2 of each oval at opposition, from published BAA reports; during the 13.3-month mean interval between oppositions, ovals with mean speed DL2 = -27.05 deg/month travel exactly 360º. Our actual tracks are not shown on this diagram, but small grey points are photographic measurements from Morales-Juberias et al.[Ref.10], adjusted to a scale with DL2 ~ -27 deg/mth, matching the BAA data. Our ovals A1 to A7 are identical to their ovals A,B,C,Z,D,E,F. At top, the year in which the BAA first recorded each oval is noted. From 1986-1988, it is unclear whether A1 and A2 existed throughout, or whether there were shorter-lived ovals which were later replaced. An earlier oval A8 probably merged with A7 in 1992 March ('M'). Dashed lines indicate intervals where the tracking of the newest and smallest oval, A4, was uncertain. Otherwise, no ovals appeared or disappeared in this time period.
(B) JUPOS chart, 1998-2003. (Chart plotted by H-J. Mettig.) 'M' indicates the merger of two ovals at the f. end of the chain in early 2002, and a probable second merger during solar conjunction. Because the chart also includes cyclonic latitudes, cyclonic oval tracks are also present and the more persistent ones have been recoloured purple or cyan for clarity.
(C) JUPOS chart, 2003-2013. (Chart plotted by G. Hahn.) AWO A0 is coloured orange-brown so that its oscillations after passing oval BA can be easily seen; track of oval BA, green; track of GRS, dark brown. Again, some cyclonic oval tracks are also present and the more persistent ones have been recoloured cyan.

Figure 7. Sets of images in 2003-2006 showing features in the S.S. Temperate domain.
(A) 2003 Dec.—2004 April. A dark brown streak or barge turns red as it fades, and then becomes a white lozenge.
(B) 2003 Dec.—2004 June. The main array of AWOs (A1-A5), with cyclonic regions between them. A cyclonic white oval between A2-A3 in Dec. breaks up into a FFR in Jan. Then a new cyclonic white oval forms between A4-A5 in Feb. (See Ref.1 for further images.)
(C) 2006 March-April. The same sectors, with a long array of AWOs interspersed with cyclonic white ovals and FFRs. [This was posted in Ref.9.]
(D) 2006 Jan.-March. Further f., including first images of new tiny oval A6, plus a new cyclonic white oval, both just passing oval BA. There is also a new, transient, rimless AWO just f. the cyclonic oval. The long-lived S3-AWO is due S of oval BA. This was at the start of the apparition when oval BA was red for the first time.

Figure 8. Set of images in 2010 Dec. showing merger of a minor AWO (A6b) with a long-lived one (A7), shortly after they passed oval BA.

Figure 9. Oscillations of a S2-AWO (A0) induced by passages past oval BA.
(Analysis by Grischa Hahn.)
(A) Table showing best-fit parameters obtained independently for longitude and latitude in each apparition, using the PERIOD program by G. Hahn. Oscillations were significant in each year except 2006.
(B) ZDP for this AWO, compared with the ZWP from New Horizons.
(C) Charts of latitude vs longitude for each apparition. Longitude is relative to the mean drift rate calculated separately for each apparition. Latitude is a rolling average and is plotted on a tenfold larger scale. In 2007, the light blue oval is the best fit from PERIOD; the phase difference (longitude vs latitude) was 38 days or approx. ¼ cycle, as the latitude correlates with the speed.

Figure 10: Longitudinal expansion of white oblongs in the SSTB.
(A) Expansion rates were measured for the 8 oblongs listed in the text. Expansion was barely perceptible when the oblong was an oval <10º long, but proceeded 0.3 to 1.4 deg/mth once the oval was longer than this threshold. In three cases when the oblong grew to 20-26º long, the expansion suddenly accelerated even more. *Right*: Examples of charts. Time is plotted downwards in units of 30 days. Length is plotted as 5-point means (blue diamonds), with individual points also plotted (mauve dots) for the A1-A2 panel.
(B) Oblong between A7-A8, plotted from 2009 April 27 to 2011 March 18.
(C) Oblong between A1-A2, plotted from 2006 May 13 to 2008 July 31.
(D) Oblong between A4-A5, plotted from 2003 Oct.26 to 2008 Nov.28.

Figure 11. The S3 prograde jet.
(A) Records of observed speeds, 2003-2012.
(B,C) ZDPs in 2005 and 2011/12 [analysis of JUPOS data by G. Adamoli].

Figure 12. Polar projection maps
(A) 2009 Sep.(including the dark debris cloud of the 'Bird Strike' impact);
(B) 2010 Sep; (C) 2012 Nov; (D) 2012 Dec. (Credits are on the maps.)
All longitudes are in System II. Latitude scale and positions of prograde jets are marked on (B). Blue arrow, long-lived S3-AWO at ~50ºS; red arrow, long-lived S4-AWO at ~60ºS; mauve arrow, secondary AWO at ~60ºS.
For earlier maps, by Cassini in 2000 and by D. Peach in 2007, see our 2007 report [Ref.4]. Partial maps plotting the expansion of the dark impact cloud in 2009 July-August were published in our report [Ref.14].

Figure 13. ZDPs for the S3 domain. [Analysis of JUPOS data by G. Adamoli].
(A) ZDP for spots in the S3 domain. Below 48ºS, all reliable tracks from 1999-2013 are shown. Above 48ºS, only data from 2011/12 are shown, for clarity; see subsequent figures for other years. Grey line, ZDP fitted by eye to these data; blue line, ZWP from Cassini. [From JUPOS/BAA report, in preparation]
(B) ZDP for the dark spots at ~49ºS, in the stationary spotty sector, 2005-2010.
(C) Example of one of these dark spots which drifted south without change of speed (the best documented case, in 2007).

Figure 14. JUPOS charts for the white oval(s) around ~50ºS (S3 domain). Charts of longitude (L2) vs. time. As in all JUPOS charts, times runs downwards and the start of each year is marked. Identified ovals are highlighted (blue for S3-AWO-1, purple for shorter-lived ones); small dots represent transient spots. [Chart by G. Adamoli]

Figure 15. The white ovals at ~50ºS. (A) ZDP for the AWOs. (B) Oscillations: Histogram of cycle lengths (for individual cycles). (C) Oscillations: Mean amplitude vs mean period, for 9 track segments spanning 1-5 cycles each. [Analysis of JUPOS data by G. Adamoli]

Figure 16. JUPOS charts for the bright oval(s) around ~60ºS (S4 domain). Charts of longitude (L2) vs. time. As in all JUPOS charts, times runs downwards and the start of each year is marked. Identified ovals are highlighted (dark blue for S4-AWO-A, other colours for shorter-lived ones); small dots represent transient spots. The track identified as AWO-A is often uncertain between apparitions due to its large changes in speed, but has been chosen to connect the largest oval in each apparition. [Chart by G. Adamoli]

Figure 17. (A) ZDP for the bright ovals around ~60ºS, from JUPOS data, compared with the Cassini ZWP. (B) Histogram of drift rates for these ovals (all white spots, 2001-2013), by number of days (blue) and number of tracks (cyan). Values indicated for DL2 (deg/mth) represent the middle of each bin. **[**Analysis by G. Adamoli]

Figure 18. Complete chart of ZDPs across the whole of the S2 to S5 domains, 34 to 66ºS. This chart shows comprehensive results for 2001-2012 when available (with a few from 1999-2013), or results for specific apparitions when only these have been analysed (2005, 2006, 2011/12). Most of the data are shown on larger scales in previous figures in this report. [Chart by G. Adamoli]
