Jupiter's high northern latitudes: patterns and dynamics of the N3 to N6 domains

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Summary

Here we present an overview of three domains in high northern latitudes of Jupiter, named N3, N4 and N5, covering latitudes 43 to 64ºN, with limited information in N6 up to 68ºN. We review their organisation and dynamics as shown by previous spacecraft, and then compare this with analysis of ground-based images in the JUPOS project. This analysis from the JUPOS database covers the years 2010-2016, with more limited data back to 1999. Analysis of the drift rates and latitudes of visible spots gives speed-vs-latitude relations for these spots (Zonal Drift Profiles, ZDP), which are close to the Zonal Wind Profile (ZWP) derived from spacecraft imagery and, for most of each domain, to the Zonal Slow Current (ZSC) derived from historical ground-based spot tracking. (The ZSC is the mean speed of the major spots in the domain, numbered accordingly; e.g. for the N3 domain, N3TC, originally N.N.N. Temperate Current.)

The N3, N4 and N5 domains all have the standard structure, the equatorward part being cyclonic and containing folded filamentary regions (FFRs), and the poleward part being anticyclonic and containing anticyclonic white ovals (AWOs) and smaller ovals. However, the two parts are not well separated in these domains, so there is some intermingling of cyclonic and anticyclonic structures, with chaotic interactions between them. It is likely that these large FFRs move with the ZSC, as well as the smaller spots that we track. We find no evidence for higher-order structures or phenomena in these domains. However, they do have individual characteristics.

The N3 domain is particularly narrow, with no retrograde jet. At times it has had numerous small AWOs, but recently spots are rather sparse though distinct, all moving with the N3TC.

The N4 domain is particularly broad and is almost filled with structures, esp. FFRs which are the broadest in any of these domains (and are the location of the most frequent lightning flashes on the planet). It has long-lived AWOs but they can be found at any latitude within the domain, shifting unpredictably, so their drift rates are very variable. Sometimes they pass each other without substantial interaction; sometimes they merge. All the FFRs probably move with the N4TC, as do the low-latitude ovals. There may be no retrograde jet except within individual FFR circulations.

The N5 domain contains some FFRs and ovals. It commonly contains 1 or 2 large AWOs, larger than any others in these domains, which are probably long-lived but cannot be tracked long-term because of their extreme and variable speeds. The organisation is similar to the N4 domain, with most features moving with a previously undefined retrograding 'N5TC', and high-latitude AWOs moving much faster.

The N6 domain approximately coincides with a visibly bland zone. We have tracked a very few features in this domain, all of them rapidly-prograding white ovals under the influence of the N6 or N7 jets. The northernmost was at 67.3ºN and drifted at -91 deg/mth, close to the N7 jet.

We have detected occasional small dark spots on the N3 jet, and one ephemeral one on the N4 jet. Otherwise, we do not detect the peak speeds of the N4, N5, N6 and N7 jets.

The drift rates of AWOs in the N4 and N5 domains, as in the N2, S3 and S4 domains, are very variable and show sudden unpredictable alternations between slow and fast rates. Circumstantial evidence suggests that some of these speed changes are caused by interactions with FFRs: specifically, that high-latitude AWOs naturally drift fast, but can be blocked by encounters with FFRs moving with the ZSC.

***Abbreviations used*:**

F., following = planetary west	P., preceding = planetary east
AWO, anticyclonic white oval	WO, white oval
FFR, folded filamentary region [cyclonic]	ZDP, zonal drift profile
ZSC, zonal slow current	ZWP, zonal wind profile

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

1. Introduction

This report on the high northern domains complements our long-term report on high southern domains [ref.1]. Comparable analysis of the N2 domain has been presented in [refs.2-5].

Figure 1 shows an overview of these domain in some of the best ground-based maps, and Figure 2 shows them in the best map from Cassini, with the prograde jets marked in red. The equatorward boundary of each domain is defined by the prograde jet with the same number; their latitudes are in **Table 1a**. For the definition and naming of the jets and domains, see [ref.1]. Most coherent spots in each domain move with a zonal slow current (for which we here introduce the abbreviation ZSC), numbered accordingly (e.g. for the N3 domain, N3TC, originally N.N.N. Temperate Current).

Table 1a. Latitudes and speeds of jets *[from ref.6]:*

Jet	Voyager, 1979 (Limaye, 1986) [From Rogers(1990, 1995)			Hubble (1995-1998) (G-M & S-L, 2001)			Cassini, 2000 (Porco et al., 2003) [Data from A. Vasavada]			New Horizons, 2007 [Cheng et al., 2008] [data from A.Cheng & A.Simon]			AVERAGE VALUES			Jet
	B"	u3	DL2	Lat.B"	u3	DL2	Lat.B"	u3	DL2	Lat.B"	u3	DL2	Lat.B"	u3	DL2	
N7				68,1	34,7	-190,7	**68,7**	**27,5**	**-156,3**				68,4	31,1	-173,5	N7
N6				63,5	21,6	-103,5	**64,1**	**17,7**	**-87,9**				63,8	19,6	-95,7	N6
N5	56,5	14,1	-59	55,3	24,1	-92,2	**55,9**	**19,9**	**-78,8**	**55,7**	**24,4**	-94,1	55,8	20,6	-81,0	N5
N4	48,2	28,5	-94	46,5	18,9	-63,2	**47,1**	**14,5**	**-50,7**	**48,0**	**23,3**	-77,7	47,4	21,3	-71,4	N4
N3	43,0	21,8	-68	42,3	26,4	-80,1	**42,8**	**18,6**	**-59,3**	**42,7**	**22,4**	-69,5	42,7	22,3	-69,2	N3

B" = Latitude (zenographic) u3 = Wind speed (m/s in System III) DL2 = Wind speed (deg/month in System II)

Table 1b. Mean speeds of Zonal Slow Currents (1900-1991) *[from ref.7, p.48]:*

	Lats.	DL2 (deg/mth)	u3 (m/s)
N3TC	44-47ºN	-15.2 (±4.1)	+2.5 (±1.4)
N4TC	49-55ºN	+1.4 (±2.8)	-2.9 (±0.9)

[& see Table 3, later in this report]

Characteristic features of all high-latitude domains on Jupiter, in spacecraft images, are chaotic cyclonic circulations called folded filamentary regions (FFRs), and well-defined symmetrical white ovals (WOs). Whenever the sense of circulation of WOs can be determined they are anticyclonic (AWOs), which can also be inferred if they lie stably within the anticyclonic part of a domain. We therefore suspect that all WOs in these domains are AWOs, but we often do not have direct evidence for this due to their small size and variable latitude and limited resolution. In ground-based images, FFRs in these domains are rarely if ever resolved, but can be identified as irregular pale patches (Figure 1).

We have already published north polar maps from hi-res ground-based images, in our final report for 2007 [ref.8], and in the following online reports which include sequences of maps over several days or weeks to illustrate the variability of the high-latitude structures:
2010/11, report no.9 (Fig.23) [ref.9 -- reproduced as Figure 1]; 2011/12, final report (no.9: Fig.35); 2014/15, final report (no.12: Fig.18).
Detailed study is on-going (see 2016/17, report no.9) in conjunction with the Juno mission.

Our methods are have been described in [refs.1, 10, 11]. As usual, all latitudes are planetographic. Speeds are given as degrees of System II longitude per 30 days (DL2, deg/mth); negative drifts are considered fast (prograding), positive drifts are slow (retrograding). DL3 = DL2 + 8.0 deg/mth.

2. Pattern and dynamics from spacecraft

Voyager produced superb hi-res images of these high latitudes [ref.7, ch.6], but these have not been fully mapped nor analysed.

Hubble images from 1994-2000 (with some hi-res ground-based images) showed several AWOs in each of the N3, N4 and N5 domains [ref.12]; some in each domain were tracked through up to 3 apparitions. They also recorded several AWOs in N6 and even further north.

The best pre-Juno map of the north polar region was produced from the Cassini images in late 2000, which is shown in Figure 2 with the prograde jets marked to identify the domains.

2.1. General structure of these domains

The N3 domain is particularly narrow. In the Voyager maps it contained 6-10 WOs of various sizes, and they were also common in Hubble images in the 1990s [ref.12], but more recently there have been fewer of them. The spots in N3 are rather sparse and small but distinct.

The N4 domain is the broadest of the northern mid-latitudes (8.4º wide; in the southern mid-latitudes, S4 is 8.3º wide and S3 is 9.5º wide). According to the Cassini map, its FFRs are wider (spanning ~6º latitude) than any others from the N1 to the N6 domains or any from the S1 to the S4 domains. The FFRs are numerous, mostly not extended in longitude, but some long ones usually exist, so there are no long-FFR-free stretches. While FFRs predominate in the lower-latitude 2/3 of the domain, AWOs are seen in the upper 1/3.

[Footnote:] As noted above, some or all white ovals (WOs) are likely anticyclonic (AWOs), although there are few images in which any spiral structure is resolved and they can lie at any latitude in the N4 domain. If they lie on the anticyclonic gradient, we can assume they are AWOs. WOs on the 'flat, slow' part of the ZDP, interspersed between the larger FFRs, are also probably AWOs, from their well-defined appearance (different from more complex light spots which are likely cyclonic), and from their vorticity as seen in the Cassini movie during interactions [see below], and from the fact that they can drift in and out of the anticyclonic part of the domain [see below].

N4 is also notable as the domain with by far the largest frequency of lightning flashes, as shown by Voyager [ref.14, & ref.7 p.287] and Galileo [ref.15]. These flashes occur in the FFRs, and one FFR typically produces many flashes per minute. Thus the N4 FFRs contain the most active thunderstorms on the planet.

The N5 domain is similar to N4 though FFRs are not so dominant nor so broad. There are always one or more AWOs (which look yellow in HST maps), some of which are larger than those in the N4 or N3 domain.

Sizes of the largest AWOs in the N5 and N4 domains were measured on HST maps listed in Section 6 (**Table 2**, below). Their dimensions in km are not as large as those of NN-LRS-1 or the largest AWOs in the southern hemisphere.

Sizes of largest ovals from HST maps (2015 & 2016)				
Domain	Length (deg)	Length (km)	Width (deg)	Width (km)
N5 (largest)	7.0	4100	2.4--2.9	3100--3700
N4 (largest 1 or 2)	4.0--5.1	3000-3800	2.1	2600
N2 (NN-LRS-1)	6.2--7.0	6000-6800	3.7--4.3	4400--5100
S2 (largest 2)	4.6--5.1	4500--5000	2.7--3.3	3200--3900
S4 (S4-LRS-1)	6.3	4250	3.3	4150

[We earlier quoted lengths of 6800-7700 km for NN-LRS-1 and 3500 km for S4-AWO-1 (ref.2). Mean sizes for ovals in all these domains are also listed in (ref.12): they report one N5 AWO as 8000 km long, 5500 km wide.]

Hubble maps and ZWPs have been published for 5 dates between 2009 and 2016 [ref.16], with maps of 2-dimensional velocity deviations from these profiles, which reveal some local circula-tions. In the S4 domain at 50-56ºS, they consistently observed a series of cyclonic circulations which coincide with the S4 FFRs; they called this 'cyclone alley'. No such consistent patterns were seen in the N4 or N5 domains, despite the numerous large FFRs here. Cyclonic circulation was clearly recorded for one N4 FFR in the 2012 Sep.20 map (Figure 4b, centre); however, some other circulations visible in their velocity maps did not coincide with distinctive visible features, whereas some visible spots (even NN-LRS-1) did not reveal vigorous circulation (Figure 4b, left). This could indicate that chaotic motions obscure circulatory patterns in these domains, but it could also be due to the limited resolution of the velocity analysis.

2.2. The Cassini North Polar Movie

An animated movie of Cassini's north polar projection maps maps in near-infrared (752 nm) dramatically shows the dynamics. The movie runs from 2000 Oct.1 to Dec.9, ending just before the hi-res colour map in Fig.2 was produced [refs.17,18]. In a single map, the jets are often hard to discern (though close inspection of the chaotic cloud patterns can usually reveal them). But in this remarkable movie, the jets can be seen all round the circumference, and jostling motions of small spots are widespread. The jets emerge as streams of small features pushing through their crowded and chaotic surroundings, like streams of people moving hither and thither in a crowded railway station. Also, the cyclonic circulation of the larger FFRs can be seen. Here we describe the visual impression of the motions (relative to System III longitude).

N3 jet: This is only apparent from individual tiny dark spots, except where a volley of small spots appears in the jet (probably from a very small N3 FFR) and they go on to interact impressively, anticyclonically, with an AWO in the NNTZ.
N3 domain: Even in the hi-res colour map, the narrow N3 domain is largely bland with only a few distinct ovals and two small FFRs. (This agrees with our ground-based tracking of the N3TC, with only

one spot in Nov-Dec.). In the movie, these features are prograding with the N3TC although perhaps not uniformly.
N4 jet: This is narrow, with chaotic interactions with flanking spots; the speed seems to be fast in some sectors but modest in others.
N4 domain: There is a very rapidly prograding large AWO, which halts when it collides with a large FFR (and the collision causes visible anticyclonic perturbation of the AWO). (We also tracked the same rapid drift and sudden halt of this AWO [ref.19].) Another, smaller WO is rapidly prograding until it is flipped round by a FFR to retrograde in the southern part of the domain. Otherwise, everything in the domain appears to be retrograding, presumably with the N4TC, with chaotic interactions at the north and south edges. The domain is more than half filled with broad FFRs, both short and long, interspersed with several small WOs in the same latitude. One of these WOs halts and is caught up in cyclonic motions of surrounding FFRs, showing anticyclonic perturbation and disruption; it may be torn apart at the end.
N5 jet: This is well-defined and fast and quite straight, though with chaotic interactions with features on its north side.
N5 domain: There appears to be a coherent retrograding current spanning the whole domain between the prograde N6 and N5 jets, with no obvious gradients. It includes one quite large AWO, and many large FFRs and small chaotic spots – with much jostling. A retrograding FFR in N5 collides with a prograding FFR on the N5 jet, and they form a combined, stationary FFR with vigorous cyclonic circulation.
N6 jet and domain: This is a narrow domain and appears as a largely bland zone, although it does contain some dark spots with much jostling. The N6 jet is not obviously distinct from the N6 domain, which is all prograding.
N7 jet: This is a very fast, vigorous, chaotic jet with many bright features moving along it at variable speeds and much movement in latitude as well, with small-scale meanderings and spin-offs by some spots.

Particular interactions of spots in this movie were catalogued by Li et al. [ref.18], who recorded hundreds of events (appearances, disappearances, interactions) and illustrated a few of them:
(their Fig.2b): A mini-FFR in the N4 domain generates an anticyclonic vortex ring in the N3 domain.
(their Fig.4a): A tiny WO on the N5 jet is destroyed by a FFR spanning the N4 domain.
(their Fig.4b): An AWO prograding in the N3 domain breaks up and disappears (possibly on encountering a low-contrast FFR).

Notably, the movie does not show the canonical zigzag pattern of zonal winds between prograde and retrograde jets. Rather, the prograde jets seem like narrow 'rivers', while the bulk of the N4 domain (dominated by FFRs) appears to move with a coherent broad retrograde current, which is the N4TC; and likewise the N5 domain. Conversely in the narrow N3 and N6 domains, all motions are prograding. All this is confirmed by ZWPs (Figure 3).

3. Relation between ZWPs, ZDPs, and ZSCs.

These domains give us deeper insight into the relationship between the zonal wind profile (ZWP) derived from spacecraft tracking of cloud textures, the zonal drift profile (ZDP) derived from JUPOS tracking of all spots, and the zonal slow current (ZSC) derived from tracking of major spots, in each domain.

Many ZWPs have been published from Voyager, Hubble, Cassini, and New Horizons, with good consistency between them. Here we show the ZWPs which included latitudes >70ºN, i.e. from Cassini [ref.20], Hubble 1996-2000 [ref.21], and Hubble 2016 [ref.22]. They are displayed in Figure 3 along with the Voyager ZWP [ref.23]. The prograde jets, which by definition separate the domains, are all sharp. The central part of each domain is marked (by definition) by a velocity minimum, but whether it amounts to a true retrograde jet as in lower-latitude domains is debatable.

In low-latitude domains (N.Tropical, N1, N2, S1), there is a sharp retrograde jet, but the ZDP is blunted, and it includes the ZSC. Sometimes we also observe a few small spots which follow the ZWP as far as the retrograde peak. The S2 and N3 domains are narrow and the velocity minimum in the ZWP does not usually extend to retrograde speed (positive DL2), but they show the same pattern of a blunter ZDP which includes the ZSC, and occasionally, slower-moving spots which do follow the ZWP to the velocity minimum. Even the S3 domain has a fairly sharp retrograde jet distinct from the ZSC, although the ZDP agrees with the ZWP (perhaps because there are few large spots in this domain).

But the high-latitude domains (N4, N5, S4) show a blunted or truncated ZWP which matches the ZDP, and the ZSC where one can be defined (N4 and now N5); no sharp retrograde jet is seen. We argue that there is no continuous retrograde jet in these domains; the modestly retrograding speed seen across the middle of the domain in the ZWP and ZDP is the drift rate of the FFRs and associated spots, thus defining the ZSC; but more rapidly retrograding speeds must exist within the FFRs as part of their cyclonic circulations [Fig.4a]. Consistent with this model is the absence of any more rapidly retrograding spots in our JUPOS data for these domains (see below), in contrast to other domains including N2 and S3 [refs.1-5].

If rapid retrograde flow exists only within FFRs, it may fail to appear in the ZWP because of the chaotic nature of these features, and/or, because the analysis is more sensitive to the boundaries of the FFRs than to their internal complexity. It would be interesting to make higher-resolution wind vector maps from the Hubble data and, best of all, from the Cassini polar movie. These would clarify the dynamics of the FFRs, test whether there is a retrograde jet, and also examine whether the hi-latitude jets vary with longitude.

4. Drift rates and zonal drift profiles (ZDPs) from amateur ground-based images

Visual observations dating from 1900-1991 [ref.7 pp.90-91] consistently defined the N3TC and N4TC (originally called NPC), which turned out to coincide with the N3 and N4 domains respectively. These are the permanent ZSCs for these domains, and they are still routinely recorded in modern JUPOS charts. In the N5 domain, no features were tracked historically, and no slow current has been defined until now [ref.7].

From 1999 onwards, and especially since 2010, our records have been extensive, due to the improving quality of amateur images and to the measurements made by the JUPOS team. Summaries of our data for all apparitions are posted in three Appendices:
Appendix 1 (.pdf) = Excerpts of text and tables from our final reports from 1999-2016, and summaries from those apparitions for which no final report has yet been produced.
Appendix 2 (.pdf) = Tables of overall drift rates for each domain from 1999-2016, from these same reports and unpublished analyses (not always precise in latitude), presenting average rates and individual tracks for some of the more conspicuous spots.
Appendix 3 (.tif) = JUPOS chart for each domain, 2009-2016. (Separate charts for the low-and high-latitude halves of each domain have been merged with different colours.)

Complete analysis of the JUPOS data for selected recent apparitions is presented here in the form of ZDPs and other charts. Complete analysis has already been posted for the apparitions of 2005, 2006, 2011/12, 2014/15, 2015/16, in our final on-line reports. **Figure 5** is a ZDP covering all of the N3-N6 domains from these data, plus a few points from 2000/01 and some other apparitions to illustrate detection of the prograde jets. ZDPs for the individual domains are shown at larger scale in subsequent **Figures 6-8**. For the N3 domain, Fig.6 uses the same data as Fig.5, as the drift rates have been well characterised and these existing analyses give a very consistent picture. For the N4 and N5 domains, tracking of features was sparse and incomplete before 2010, but much better from then onwards; so we show analysis of all JUPOS data from 2010-2016.

The prograde jets in these latitudes (N3 to N7) do not display outbreaks of distinct spots, and we seldom if ever detect a spot moving with the peak jet speed, but some spots (esp. white ovals) have rapid speeds close to the peaks.

4.1. N3 domain

The N3 jet peak (43ºN) has occasionally been revealed by single small dark spots at 42-43ºN (**Figure 6a**); ten are tabulated in Appendix 2. Their drifts range from DL2 ~ -40 up to -78 deg/month.

The N3TC: Historically this has been a steady current with mean DL2 = -15.2 [ref.7 & **Table 1b**]. Some spots have been tracked in all years since 1999, increasing from 5-6 per apparition in 1999-2002 to 11-29 in most recent apparitions. The majority of them have very consistent speeds with a mean DL2 = -18.6 (±2.3) (1999-2016) (**Figure 6b,c**), and they are clustered close to the velocity minimum at 45ºN. A minority have significantly faster speeds, on both the cyclonic and anticyclonic sides.
Within the dominant population of N3TC spots, white and dark spots occupy the same latitude range, not showing the usual segregation into anticyclonic and cyclonic half-domains respectively. (Indeed in 2003/04 the white spots were southerly and the dark spots northerly, opposite to the expected pattern.)
Most spots fit a consistent ZDP which is similar to the Cassini (and Voyager) ZWP but slightly blunter, i.e. it does not extend to such slow speeds, apart from 3 minor spots in 2011/12 which did match the Cassini velocity minimum of DL2 ~ -4.
Speeds on the anticyclonic side have ranged up to DL2 = -42, i.e. on the south flank of the N4 jet. But there does not seem to be a distinct class of fast spots.

The JUPOS chart (Appendix 3) reveals two examples of dark spots turning red before they disappear, one in 2009 and one in 2011/12. This phenomenon is common for cyclonic dark spots in other domains [ref.1].

The N4 jet peak (47.4ºN) has only once been seen, for an ephemeral tiny dark spot with DL2 ~ -70 at ~47ºN in 2007 (not plotted). (An AWO which crossed the jet from the N4 to the N3 domain, in 2011/12 [see below], did not exceed DL2 = -34 as it did so)

4.2. N4 domain

In the N4 domain, we find that most spots belong to the historically defined N4TC, which coincides with the very blunt velocity minimum of the Cassini ZWP. We argue that this is the drift rate of the numerous FFRs which dominate this domain, and that there is no real retrograde jet. However, the most conspicuous and long-lived spots are white ovals which have very variable speeds; sometimes they move with the N4TC and mingle with other N4TC spots, but often they move much faster and are further north in the anticyclonic part of the domain. Often they shift between fast and slow speeds, and accordingly in latitude.

Our reports from 1999-2016 (Appendix 2) show that the majority of well-defined spots had speeds consistent with the N4TC (see **Table 3**, below), especially up to 2012. The historical mean speed was DL2 = +1.4 (±2.8) deg/mth (1900-1991), mainly derived from dark spots [ref. 7]. There seems to have been a slight deceleration in recent decades, as our mean of apparition means is +3.3 (±1.4) (1999-2003), and +5.5 (±1.0) (2003-2016). The latter figure agrees with the peak found from all JUPOS measurements of the N4TC (see below): DL2 = +6 (2010-2016). The difference could represent a real secular change, or it could indicate that the historical values included tracks with brief prograding intervals that were not resolved.

Faster-moving spot tracks were also recorded in some but not all apparitions from 2000-2012; but then a change occurred. In 2012/13 the numerous slow (N4TC) tracks common in previous years – which included the largest WOs, as well as many dark spots -- were largely absent! Instead, WOs with fast speeds dominated. Of the 4 best-tracked WOs in 2012/13, only one was consistently in the N4TC; another accelerated up to fast speed, and two others had fast speeds, with fluctuations, for most of the apparition, up to DL2 = -12.4 and -31. Since then, although slow (N4TC) spots have again been regularly seen, the most conspicuous white ovals have been fast-moving for most of the time, with DL2 from -12 to -44, even though they still shift to slow speeds for short intervals.

One of the fastest tracks was recorded in 2000/01, as we tracked the same AWO that was moving very fast in the Cassini movie. It had DL2 = -47 at 54.4ºN until the end of Nov. when it suddenly halted, to DL2 = -2 at 53.5ºN [ref. 19]. Since 2010 we have only tracked one feature faster than this, DL2 = -56 in 2012/13. Otherwise the fastest was DL2 = -44 in 2013/14.

One oval (WO-A, the most prominent oval in each apparition) could be tracked from 2006 to 2008 with a steady slow drift, with only brief fast segments in 2006 and 2007; and probably likewise into 2009. It may have persisted into 2010, but then accelerated to a more sustained fast speed and interacted with other WO(s), one of which probably persisted as the most conspicuous WO in 2011/12. This and other WOs may have persisted thereafter, but speeds were much more variable so it was not possible to confirm their identity.

Since 2010, there have always been 2 or 3 WOs which have been tracked through most or all of each apparition. (In earlier apparitions, sometimes there was only one.) None have definitely appeared or disappeared within an apparition, except for the one which was ejected to the N3 domain in late 2011 [Section 5 & Appendix 1]. So these large WOs probably last for much longer than a year. However, because of their rapid unpredictable changes of speed, it has not been possible to connect them up between apparitions, except for a probable link in 2014. From their latitudes when moving fast, we deduce they are anticyclonic, as also indicated by their classic AWO morphology [see HST maps, below].

The full analysis of JUPOS data 2010-2016 (Appendix 3) tracks many white spots, as well as small dark spots, but most of the tracks are sparse and short, and rather uniformly slow (DL2 ~ +2 to +10, i.e. the N4TC). These are small spots, and may be genuinely short-lived, or they may disappear from view because of suboptimal resolution or change of appearance. Dark spots, in particular, are rarely tracked for more than 1 or 2 months close to opposition. These N4TC spots can lie at almost any latitude in the domain except the northern fringe. Sometimes they change latitude, smoothly or abruptly, without changing their drift rate. Thus they have some freedom to move within this domain.

The results from all the apparitions fit a consistent ZDP [Fig.7, top], which agrees well with the Cassini ZWP. The expected anticyclonic gradient is seen from 53 to 55ºN; in this range, all tracked spots are bright, presumably AWOs. (A systematic offset of ~0.5º latitude along this gradient could be due to small systematic error in one or both data sets at this high latitude.) There is no difference in ZDP between long-lived (large) AWOs and other white spots [data not shown]. However, from ~50 to 53ºN there is no gradient and no sharp retrograde jet. Spots in this range are both bright and dark, and we do not know their vorticity. They may fall into two clusters, above and below 51.2ºN, but even if this is a real division, it does not indicate whether they are cyclonic or anticyclonic, as AWOs have been recorded as far south as 51.0ºN [see sections 5 & 6 below].

Histograms of speeds [Fig.7, bottom] confirm the visual impression that the speeds are bimodal, with peaks around DL2 ~ +6 and -26. Most spots (including all the dark spots) are slow, with a peak between DL2 = +2 and +10. These probably represent the bulk motions across most of the domain, including the large FFRs which we cannot track as such; this speed range defines the N4TC. There are also many white spots with fast speeds, ranging up to DL2 = -56, all on the anticyclonic gradient in the northern part of the domain (except for the spot which shifted to the N3 domain). Their peak frequency is between DL2 = -22 and -30. Both speed groups are more distinct when plotted by total duration of tracks than by number of tracks, implying that the speeds near DL2 ~ +6 and -26 are not only more frequent but also more persistent. It looks as though the slow speeds (N4TC) are more constant than the fast speeds. Some modest prograding speeds occur but not stably.

The N5 jet (56ºN): The fastest, northernmost white spots of the N4 domain are on the south flank of the N5 jet, with DL2 ranging up to -56 at 54.7ºN (2012/13) [see magenta entries in Appendix 2 table]. We have not observed the peak of the jet. On the north side, the fastest spot recorded had DL2 = -39 at 56.1ºN (2011/12).

4.3. N5 domain

Historically, no spots were tracked north of the N4 domain, so the N5 domain was unknown. Spacecraft ZWPs defined it clearly, with a profile similar to that of the N4 domain, likewise centred on a blunt, modestly retrograde flow. Small bright spots measured on Voyager maps at ~61-62ºN had DL2 = +10 to +27, consistent with this flow [ref.7, p.83].

Now that we have extensive ground-based observations, we find that, as in N4, most spot tracks have positive DL2 (they are at 59-61ºN) and their ZDP has the same blunt retrograde form as the ZWP (Fig.8, top). We therefore suggest that the domain structure is the same: this blunt retrograde current is a ZSC (to be named the N5TC) and there is no true retrograde jet, apart from presumed circulation within the FFRs. Also as in N4, from 2010 onwards we have recorded white spots at higher latitudes (62.5—63.5ºN) with much faster speeds (DL2 = -10 to -57). There is no difference in ZDP between long-lived (large) AWOs and other white spots [data not shown].

Mean drift rates recorded for two long-lived AWOs in Hubble images in the 1990s (DL2 = +9.2 and +11.1) [ref.13] were typical of our newly defined N5TC, suggesting they did not have fast track intervals in those years.

The mean speed of the N5TC from 2000-2016 was DL2 ~ +12. In 2000-2004, and again in 2013-2016, just 1-3 spots were tracked in each apparition, and they were almost all white ovals clustered tightly around DL2 = +9.8 (±1.8). In 2010-2013, more spots were tracked including some dark ones, and the mean speed was slower, DL2 ~ +14.

Looking at the statistics of the speeds (Fig.8, bottom), for white spots, there is an obvious peak of both track numbers and their duration around DL2 = +13. There is a long 'tail' toward prograde speeds, as for the N4 domain. There is a hint of a second peak around DL2 = -15, but it is doubtful, and more apparent with track frequency than duration. There is a minor group of fast speeds around DL2 = -48. There is little to say about dark spots, except that they also peak at about DL2 = +13. Averages are as follows:
Mean of all spots between 58.0 and 62.0ºN (except 2 outliers): DL2 = +12.7 (±4.2) (N=33).
Mean of all spots between 63.0 and 65.0ºN (except 1 outlier): DL2 = -48.0 (±5.3) (N=5).

Although the vorticity of spots in this domain cannot be identified from ground-based images, we assume that white spots are likely to be AWOs if they are prograding on the anticyclonic gradient at >62ºN, and/or if they are long-lived. When fast AWOs decelerate to N4TC speed, in accordance with the ZDP, we find that they can descend as low as 60.1ºN latitude; and latitudes of long-lived white spots can be as low as 59.3ºN. So, most or all white spots above 59.3ºN (the middle of the retrograde current) may be AWOs [consistent with Hubble maps – see below]. No white spots have been definitely record-ed between 57.7 and 59.0ºN, which may be a natural division. So white spots at 56.1—57.6ºN, which are on a strong cyclonic gradient, are probably cyclonic, although we have no hi-res views of them.

The N6 jet (64ºN) and domain: Fast speeds in the N4 domain have been recorded up to DL2 = -57 at 63.5ºN (2012/13). We have also, rarely, recorded very fast speeds for white spots on the north flank of the N6 jet: DL2 = -47.6 at 64.5ºN, and -56 at 65.4ºN [see magenta entries in N5 table in Appendix 2]. These data do not clearly locate the jet peak, which may be because of imprecision in such high latitudes, or it could be due to real nonuniformity in this jet [see Cassini review above].
The N7 jet (68.4ºN) was clearly indicated by one white spot in 2011/12. It had the highest latitude and fastest DL2 of any spot recorded in these northern domains: -91 deg/mth at 67.3ºN! Later it decelerated to -47 deg/mth at 66.5ºN.

4.5. Discussion: Comparing speed ranges for AWOs in high-latitude domains:

The N4 and N5 domains thus have very similar dynamical patterns to the N2, S3 and S4 domains (**Table 3** below). In all of them, AWOs often switch between fast and slow speeds, sometimes suddenly and unpredictably, and sometimes according to a semi-periodic oscillation. The slow drifts match the

ZSC, while the fast drifts cover a wide range, but in most cases do cluster around a distinct fast peak. The N2 and S3 domains also have a slower (retrograde) jet which we occasionally detect with small dark spots in specific sectors; we suspect that these are spots emitted from FFRs [refs. 1 & 5]. These are not seen in the N4 and N5 domains.

Table 3.

Summary of drift rates in high-latitude domains (ZSC & faster): DL2 (deg/30d)											
			Zonal Slow Current								
	Historical		*Recent*		*JUPOS*		*JUPOS*		*JUPOS*		*Data*
	(Rogers 1995)	*SD*		*SD*	*slow peak*	*SD*	*fast peak*	*SD*	*fastest*		*source*
N5	--		+12	3	+13	4	-48	5	-57		this report
			(2000-2016)								
N4	+1,4	2,8	+5,5	1	+6	3	-26	2	-56		this report
	(1900-1991)		(2003-2016)								
N2	-0,3	3,2	-1,3	2	-2	2	-12	3	-22		Rogers et al.(2011) JBAA
	(1900-1991)		(1996-2008)								
S3	-8,3	5,7	--		d.ss: -10	4	-25		-56		Online long-term report
	(1900-1979)				AWOs: +2						
S4	--		--		d.ss: var.		(no peak)		-47		Online long-term report
					AWOs: ~0						
	*Standard deviation of apparition means or (for recent analysis) of individual spots in a defined range.										

5. Particular interactions of spots

Many interactions were recorded in the Cassini movie, as described in Section 2.
Hubble images in 1995 showed how a long-lived, retrograding AWO in N5 merged with a much smaller prograding AWO [refs.12 & 13].

In our summaries of each apparition, we have noted the following interesting interactions (more details are in quoted in Appendix 1):

N3 & N4 domains:

2007 final report: We noted an apparently coordinated outbreak and acceleration in a sector of the N3 and N4 domains.

2011/12 final report: One AWO crossed the N4 domain and N4 jet as it interacted with a FFR, and was transferred into the N3 domain! This is the only such event that we have recorded.

2014/15 final report: Detailed accounts were given including, for the N4 domain:
AWO-a (fast, northerly) passed w7 (slow, southerly) in early Feb; w7 moved N from 51.0 to 52.5°N at this time without change of speed. AWO-b had a fast run and then underwent 3 cycles of oscillation between fast and slow drift rates with period 25-30 days. AWO-c had fast drifts except for a 3-week slow phase while it was on the N edge of a large FFR.

N5 domain:

2010 Sep.: A long-lived N5 AWO at ~62°N retrograded to L2 = 310 then instantaneously reversed and moved N to prograde rapidly. As shown on polar projection maps (Fig.1), it was a small AWO with dark rim, but we could not see any reason for its sudden acceleration.

2011 Aug.: Prograding and retrograding WOs passed each other, producing only temporary oscillation in the drift rate of each.

2011 Oct: A tiny retrograding AWO at 61.6°N collided with a prograding light cyclonic patch at 57.0°N, and they both disappeared, possibly destroyed by the interaction.

2012 Sep-Dec: Two WOs [w1, w2] passed each other in early Sep., then changed drifts and eventually merged on Dec.15 [Figure 9].

N4 domain (cont.): According to the complete JUPOS chart (Appendix 3), encounters between fast and slow WOs are quite frequent; from 2010-2016, we note 12 definite well-observed examples (plus another 4 where the outcome was unclear). In 7 of the 12 examples, the ovals passed each other without major changes of speed. This does not happen in most domains, but in the N4 domain, the fact that AWOs with different speeds can be widely separated in latitude means that they can pass each other without interacting. In the other 5 examples, one or other oval disappeared, so they may have merged; in 3 cases the fast one survived, in 2 cases the slow one. (We have also reported several such encounters in 2017 [Report no.9], whose component ovals can be identified as AWOs in Juno images; further analysis is in preparation.)

Conversely the sudden decelerations and accelerations of white spots are not generally associated with encounters between them (although in some case there are a few points on the chart suggesting that a second small spot could have been involved). Instead, we suspect that decelerations are often due to encounters with FFRs. In our 2015/16 final report [ref.5 & Appendix 1], for the N2 domain and others, we proposed that AWOs are naturally prograding but can be temporarily held up by FFRs which belong to the slow current for the domain; also by small retrograding dark spots [ref.4]. In the N4 and N5 domains, we find several examples which seem to illustrate this behaviour: we noted two examples in the Cassini movie, and circumstantial evidences suggest several other examples in our data, including correlation with Hubble maps (see below).

6. Hubble maps correlated with JUPOS charts

To understand the nature of features in these domains in more detail, I compared maps made from Hubble Space Telescope images with the contemporaneous JUPOS records of the spots. The maps were made from images on the following dates:
2012 Sep.20 (map by Marco Vedovato) [ref.24]; 2015 Jan.19 [refs.25 & 26]; 2016 Feb.9 [ref.26].
In **Figures 10-12** these maps (with south up) are aligned with the JUPOS charts of the N4 and N5 domains (from Appendix 3) to identify the spots which we tracked.

N4 domain:

Arrows indicate the spots which we tracked, colour-coded as in the JUPOS chart (light blue for low latitude and slow-moving, green for high latitude and fast). The spots tracked by JUPOS can easily be identified as the most conspicuous spots in the domain, with relative latitudes consistent with the JUPOS data.

In the 2012 Sep.20 map, all 5 of the well-tracked white spots are seen as well-defined WOs, including one which was particularly far south, at ~50ºN. One other white spot, whose JUPOS track was unclear around Sep.20, appears as an irregular white patch, and two tracked dark spots are compact irregular dark patches.
In the 2015 Jan.19 map, likewise, 5 well-tracked white spots are seen as well-defined WOs, whether they were rapidly prograding at 54.5—55ºN, or retrograding at 52.5ºN; conversely a sparsely-recorded white spot is a chaotic feature, possibly a mini-FFR, while a tracked dark spot is well defined.
In the 2016 Feb.9 map, 3 tracked white spots appear as (yellow) WOs, probably AWOs. One or more other white spots, with N4TC drifts though not thoroughly tracked, appear more complex so are likely to be cyclonic.

The 2015 Jan.19 map provides a probable explanation for the oscillation in speed and latitude of AWO-b in that apparition. From Jan.10 to April 1, with a mean DL2 of -22, it performed 3 cycles of oscillation with periods of 23-33 days. In the Hubble map, AWO-b is seen to be passing a row of mini-FFRs (5 to 7 of them, spaced ~23-27º apart in longitude). If we assume a typical DL2 of +7 for the FFRs, the mean relative speed was 29º/30d, so AWO-b would pass one FFR every 24-28 days. As this is essentially the same as its observed period of oscillation, we conclude that the oscillations in speed were probably caused by its repeated encounters with these FFRs.

N5 domain:

The 2012 Sep.20 map was made just after spots w1 and w2 had passed each other. The fast-prograding w1 is a large AWO*. The slower w2 is one of two small AWOs, which probably merged soon after to form w3. The very fast WO w5 (DL2 = -56, 65.4ºN, i.e. in the N6 domain) is indeed just N of the N6 jet, in contact with a smaller, slightly irregular WO which was retrograding in the northern N5 domain (possibly an AWO recently disturbed by their conjunction).

In the 2015 Jan.19 map, there are just two tracked white spots, which were prograding at the time; they appear as yellow AWOs *.

In the 2016 Feb.9 map, again there are just two tracked white spots, which are large yellow AWOs*. Their large distinct oval forms suggest that they were long-lived.
On the JUPOS chart, both had only just appeared and were roughly stationary, but it seems likely that both spots existed earlier with poorly-characterised rapid prograde drifts, and had just halted within the previous few days. The larger one was temporarily invisible from the ground, probably because of its low contrast; it was probably spot w1 which had rapidly prograded to become w2, possibly halting at the following end of a FFR.

*These large AWOs are positioned on the N edge of the N5 domain, straddling the expected latitude of the N6 jet, although they were not moving with full jet speed, which suggests that the N6 jet may not be uniform at all longitudes.

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Figures

[Note: Different figures have different orientations!]

Figure 1. North polar maps from some of the best amateur images (from our report, ref.9 Fig.23). It includes FFRs in the N4 domain changing shapes over just a few days, and an AWO in the N5 domain which had just reversed its drift.

Figure 2. North polar map from Cassini (*Credit:* NASA/JPL/Cassini imaging team, PIA07783), with prograde jets marked.

Figure 3. Zonal wind profiles from spacecraft.
Top: Voyager (1979; red) and Hubble (1995-1998; black) (adapted from ref.21).
Bottom: Cassini (2000; black) and Hubble (2016; blue) (adapted from ref.22).

Figure 4a. Proposed arrangement of currents in N4 and N2 domains. In the N2 domain, the ZWP indicates a sharp, continuous retrograde jet, but the ZDP is blunter, thus encompassing the ZSC (NNTC) which governs the motion of large belt segments and FFRs. In the N4 domain, the ZWP is the same as the ZDP, with a blunt profile that coincides with the ZSC (N4TC) that governs the motions of the large FFRs and some AWOs; but faster retrograde winds presumably occur within FFRs (Fig.4b). (The background cylindrical map is from Cassini: NASA PIA07782, edited.)

Figure 4b. *Top*, part of map from Hubble on 2012 Sep.20 (ref.24; see also Fig.10, inverted). *Bottom*, coincident map of velocity deviations from the global ZWP shown at right, colour-coded as at top right; small arrows indicate the local velocities. (Adapted from ref.16.) Asterisks indicate matching points: black, cyclonic (large FFR near centre, more complex at left); magenta, anticyclonic (NN-LRS-1, circulation not resolved).

Figure 5. Zonal drift profile from JUPOS data. (Open symbols are imprecise.)

Figure 6a. Excerpts from JUPOS charts showing spots on the N3 jet, on a longitude scale moving at DL2 = -38 deg/mth. DL2 for each spot marked is shown in magenta.

Figure 6b. *Top:* Speed of N3TC, 2000-2016, from JUPOS data.
Bottom: ZDP of N3 domain, 2005-2016, from JUPOS data.

Figure 7. *Top:* ZDP of N4 domain, 2010-2016, from JUPOS data. *Bottom:* Histograms of speeds; (a) by number of track segments measured; (b) by total duration of tracks measured.

Figure 8. *Top:* ZDP of N5 domain, 2010-2016, from JUPOS data. *Bottom:* Histograms of speeds; (a) by number of track segments measured; (b) by total duration of tracks measured.

Figure 9. Amateur images showing two N5 AWOs merging in 2012 Dec. NN-LRS-1 (then a red oval) provides a reference point. South is up.

Figure 10. Hubble map from 2012 Sep.20 [adapted from ref.24] aligned with JUPOS charts of N4 and N5 domains [excerpts from Appendix 3]. To align with the JUPOS charts, the map is shown with south up. Latitudes of the prograde jets are marked. Arrows mark spots which can be tracked on the JUPOS charts (green, cyan and black for N4; white for N5).

Figure 11. Hubble map from 2015 Jan.19 [adapted from refs.25 & 26], aligned with JUPOS charts of N4 and N5 domains, as in Fig.10. (The latitude scale was fitted to this map approximately and appears to be ~1 deg too low by comparison with the visible jets.)

Figure 12. Hubble map from 2016 Feb.9 [adapted from ref.26], aligned with JUPOS charts of N4 and N5 domains, as in Fig.10.