Final version, 2013 July 14

Jupiter's South Temperate domain: Behaviour of long-lived features and jets, 2001-2012

John Rogers , Gianluigi Adamoli, Grischa Hahn, Michel Jacquesson, Marco Vedovato, & Hans-Jörg Mettig

(JUPOS team and British Astronomical Association)

Summary

This report gives an overview of Jupiter's South Temperate domain, covering the years 2001-2012, from amateur images and the JUPOS database. We summarise the long-term history of the major features, principally a succession of structured cyclonic sectors in the South Temperate Belt (STB), one of which is associated with the single large anticyclonic oval (oval BA); and the STBn jet that is associated with them. Informative comparisons can be made between the speed-vs-latitude relationship for individual spot(s), which we here define as the Zonal Drift Profile (ZDP), and the speed-vs-latitude relationship for the smallest cloud features, which is the Zonal Wind Profile (ZWP). We provide a synthesis which explains most of the previously puzzling features of this domain.

The STB consists of alternating structured and undisturbed sectors, and we track the origin and fate of the structured segments over the years. At the preceding end of one of them is oval BA, the only large anticyclonic oval in the domain. The other structured sectors consist of cyclonic regions, which begin as small dark spots or streaks remote from oval BA, then expand, and eventually catch up with the dark segment following BA, inducing intense disturbance in and around it. This cycle has been completed three times in 15 years.

Oval BA has been reddish since 2006. It sometimes undergoes large changes of drift rate, which appear to be caused by two factors: the cyclic impacts and shrinkages of structured STB segments impinging on its following side, and the periodic passages past the Great Red Spot. From 2008 onwards it has been shrinking in length and probably in width, which accounts for a progressive southwards shift in its zonal drift profile [speed-vs-latitude relationship]. The same evolution was shown by the three earlier long-lived ovals.

The retrograde STBs jet and the prograde STBn jet are both shown to vary with longitude and time. The ZDP for dark spots in the STBs jet and STZ varies with longitude (in relation to the 'STB Remnant') and with time, suggesting that the ZWP also varies. Spacecraft data show that the STBs jet is often faster in structured sectors; so is one component of the STBn jet.

The STBn jet, as observed by spacecraft, has two sub-peaks at ~26ºS and 29ºS. We show that the 29ºS subpeak is relatively stronger alongside STB dark segments, and that the speeds of these sub-peaks also vary with time. The STBn jet often carries small dark spots, emanating from long-lived dark STB segments, and we show that they tend to drift northwards during their lives, probably from one sub-peak to the other. These results reveal a novel longitudinal and latitudinal structure in a prograde jet.

An Extended Summary (3 pages inc. summary figures) is posted separately:
Part I [= EPSC abstract], Oval BA and the cyclic development of structured sectors;
Part II, Variations of the STBs and STBn jets with longitude and time.

References, Tables, Figure legends, & Appendices 1-3, are at the end of this file.

Appendix 4 (excerpts from previous interim reports) is in a separate DOC file.

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

1. Introduction

The immense size of Jupiter's atmosphere is matched by the long time-course of many important phenomena within it. While observers and recorders tend to focus on events one year at a time, major atmospheric features exist and evolve over much longer time-scales, and develop in systematic ways which are not always recognised in the short term. Here we present a longer-term view of the South Temperate domain.

The history up to 1991 was described in [ref.1]. 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 1999/2000, 2000/01, and 2001/02 [see 'Publications' on this BAA web site (http://www.britastro.org/jupiter); inc. refs.2-4]. Since then, we have posted many interim reports [see 'Reports' on this BAA web site; and list in References below], but have not had time to post final reports except for a few apparitions (esp. 2007) and specific phenomena. However, the JUPOS project (http://jupos.org) has compiled data and charts for all latitude bands since 1998, which form the basis of the present survey.

In this report, we present a survey of the S. Temperate domain since 2001, including analysis of the JUPOS charts, and special analyses by JUPOS team members which reveal novel dynamical processes. This survey starts in 2000/01 so that it can be connected to our previously published reports [refs.2-4] and to the maps from the Cassini spacecraft in 2000 [refs.3 & 5]. It ends in 2012. We will also soon post the full report for the 2011/12 apparition, and a companion report on the long-term features of the three domains further south.

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). 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.

In WinJUPOS, each image is fitted to an elliptical outline frame, after brightening to reveal the limb, and the alignment can be checked by reference to positions of satellites and their shadows, and to positions of well-known features. The brightness range is adjusted so that the atmospheric features are most clearly visible. The measurer then positions the cursor over every distinct feature ('spot') in turn and its longitude and latitude are automatically displayed, and can be recorded into a database. Data over several months or years are then selected by latitude range and plotted as longitude-vs-time charts, on which individual spots are evident as linear arrays of points. These are further analysed to extract more precise drift rates and latitudes for individual spots.

The frequency and quality of images has improved progressively over these 12 years, esp. 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 many very small features have been tracked recently.

Uncertainty in latitude is estimated from the scatter of measurements: for each spot, typically ± ~0.4 ° standard deviation, and ≤0.1° standard error of the mean because many measurements (usually >8) were averaged for each spot. Uncertainty in drift rate is conservatively estimated as 2 x 0.4° divided by track duration in months; nominal uncertainty for a 1-month track is thus 0.8°/month, but over longer intervals the precision is usually limited by real fluctuations in drift rate.

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.

***Abbreviations used*:**
AWO, anticyclonic white oval
F., following = planetary west (right)
Np., north-preceding (north-east)
ZDP, zonal drift profile
v.d.s., very dark spot
STB, South Temperate Belt
STBn, north edge of STB, and its associated jet
GRS, Great Red Spot
P., preceding = planetary east (left in images)
Sf., south-following (south-west)
ZWP, zonal wind profile
STC, South Temperate Current
STZ, South Temperate Zone
STBs, south edge of STB, & associated jet
--and other standard abbreviations for belts and zones, given on this BAA web site under 'Programme'.

3. Background

3.1. Zonal wind profiles and zonal drift profiles

The atmosphere of Jupiter is divided into dynamical units occupying fixed latitudinal bands or 'domains', separated by prograde (eastward) jets [refs.1 & 6]**.** The S. Temperate domain is bounded by the SSTBn jet at 36°S and the STBn jet at 26-29°S **(Table 1 & Fig.2)**. (As we shall see, the STBn jet is an exception to the general rule that prograde jets are narrow and fixed in latitude.) The domain is bisected by the retrograde (westward) jet at 32°S, separating the S. Temperate Belt (STB), which has cyclonic shear, from the S. Temperate Zone (STZ), which has anticyclonic shear.

In all Jupiter's domains, the wind jets and gradients as outlined above constitute the Zonal Wind Profile (ZWP), deduced from spacecraft tracking of the smallest cloud features or textures.

Conversely, ground-based observations track distinct features ('spots'), which are circulations or waves, so their drift rates may differ from the surrounding wind speeds. Indeed the larger features visible in a domain usually have similar speeds regardless of latitude, defined as the 'slow current'. Thus, large features of the STB or STZ move with the S. Temperate Current, with DL2 ~ -10 to -17 deg/mth, so they overtake the Great Red Spot every 2 years or so.

As the resolution of images and of measurements has improved in recent years, we can now track not just the average motions, but variations for many individual spots, and we also track smaller and smaller spots, whose speeds vary with latitude in the same sense as the ZWP, but often with shallower gradients. Here we define the speed-versus-latitude relation for tracked spot(s) as the Zonal Drift Profile (ZDP). For the smallest features, this is the same as the ZWP. Scatter in the speed-vs-latitude charts will be shown to be partly due to variations in the ZDP between different longitude sectors, and different years, and different sizes of spot.

The co-existence of the slow current and the ZWP has been explained as follows [ref. 7]. Anticyclonic ovals all obey ZDPs which are parallel to the ZWP or somewhat shallower; but the ZDPs for the larger ovals are displaced to lower latitudes (probably because the ZWP is locally distorted around them), so ovals with different sizes and centre-latitudes still have similar speeds. Large cyclonic features tend to lie in a narrow latitude band which has a fairly constant zonal speed, and all cyclonic features obey ZDPs which become shallower than the ZWP as they approach the retrograde jet, so the full retrograde jet speed is rarely detected.

3.2. The S. Temperate domain, 1950-2000

The typical appearance of the S. Temperate domain has evolved over the years [ref. 1]. In the 1950s and 1960s, the STB was usually a conspicuous dark belt, and the major features on it were the three great anticyclonic white ovals (AWOs), widely spaced in longitude, which were gradually shrinking. In the 1960s and 1970s, it was common for a sector of STB between any two of the great AWOs to fade (whiten), and Voyager showed that such a 'STB Fade' was a closed cyclonic circulation. From 1975 onwards, STB Fades repeatedly induced darkenings of the adjacent S. Tropical Zone as they passed the GRS, called S. Tropical Dislocations. Also from 1975 onwards, one STB Fade progressively lengthened over the next 15 years, until it extended more than half way round the planet, and residual segments of dark STB f. the long-lived AWOs tended to shorten, so that from 1989-1992 the STB was nothing more than a very tenuous STB(N), except for short dark ovals or streaks f. the AWOs.

Meanwhile, the three AWOs, shrinking, began to drift closer together: two of them came together as a stable pair in 1989, and they were joined in the mid-1990s by the third one plus a smaller AWO, forming a chain alternating with several cyclonic ovals of various colours **(Fig.1A)** (& Appendix 1: The Morphing Spot). Long dark STB segments had reappeared, but gradually rearranged into a single STB segment f. the chain of ovals, shortening. Then in early 1998, the first two AWOs merged, and in early 2000, the resulting oval merged with the third one in turn, producing oval BA as the only remaining large AWO, with a short dark STB segment f. it [refs.2,8,9]. Meanwhile on the other side of the planet, three very dark spots appeared in 1997-1998, which were the precursors of the next dark STB segment **(Fig.1B).**

3.3. The S. Temperate domain, 2000-2012

A recurrent feature of this story in the 1980s-1990s was the tendency of dark STB segments to lie f. the long-lived AWOs, and to gradually contract to just a small dark patch. This phenomenon has also dominated the STB more recently. Since 2000, the STB has always consisted of several contrasting sectors: structured sectors (often broad dark STB segments, with cyclonic disturbance) alternating with longer undisturbed sectors (largely featureless apart from a tenuous STB(N)).

There are always 2 or 3 structured sectors. One of them is headed by oval BA at its p. end, followed by a dark STB segment (segment A) (often having a much smaller, shorter-lived AWO to its south), although the dark STB segment sometimes contracts to form a small dark cyclonic oval (barge). The other structured sector(s) are organised only in the cyclonic (belt) latitudes **(Fig.2)**; there are no substantial AWOs associated with them (unlike in the decades up to the 1980s). Some structured sectors are dark STB segments, but one was very pale and quiet, viz. the 'STB Remnant' in 2005-2010.

Dark STB segments usually look spotty at the smallest scale in very-hi-res images. They emit small dark spots from the Np. corner onto the prograding STBn jet, and irregular dark spots or streaks from the Sf. corner into a slower-moving current (usually not quite as slow as the retrograding STBs jet), where they constitute a dark extension ('Sf. extension') or STB(S) 'tail'. This extends across the retrograding jet, and small anticyclonic rings or AWOs sometimes form within it. Dark STB segments are shown in spacecraft images to have intense small-scale turbulence within the cyclonic belt, from which these spots are emitted. All this activity was most graphically shown in the Cassini movies, and has also been confirmed by JUPOS measurements in many apparitions since. **Figure 2** shows details of a typical STB structured sector, and the positions of the jet streams, on a portion of the Cassini map.

Methane-band images (0.89 µm wavelength) give further insight into the structure of this domain. In other domains (the N. Temperate and N. and S. Tropical domains), methane-band patterns tend to be uniform around the planet and only weakly reflect visible changes in brightness, suggesting that the methane-bright haze is influenced more by the zonal wind profile than by the visible weather systems. In contrast, the STB is methane-dark and broad in the structured sectors, but light in the undisturbed sectors apart from the tenuous STB(N) which is methane-dark. The STB Remnant was as fully methane-dark as any other structured sector (e.g., sets of methane images in our 2008 and 2010 reports: see 'Reports' on this BAA web site, and list in References below). This suggests that the ZWP may be different in these sectors, consistent with our inferences about the sector structure of the STBn jet (section 7 below).

Figure 3 shows one of the best available maps for each apparition from 2000 to 2012, with the S.Temperate features labelled. **Figure 4** shows the complete JUPOS charts. Some significant interim reports on our web site are listed in the References and text from them is reproduced in **Appendix 4**. For image compilations of specific phenomena, the reader is referred to our on-line reports; but this report includes several image compilations from the 2003/04 apparition (Figs.6 & 7A), since some of these were not compiled at the time, and those which were are no longer on our web site, and this apparition included several important phenomena in these domains.

4. Structured sectors of the STB

The one persistent sector of STB is f. oval BA, and here we call it STB segment A. The other structured sectors drift with DL2 = -16.7 (+/-1.0) deg/mth, faster than segment A, and so catch up with it and merge with it with dramatic effects, as happened in 2003 and 2010 (and now in

2013). While this happens, another structured sector arises from some small cyclonic feature on the other side of the planet. (Sometimes this is a very small, very dark spot (v.d.s.) , presumably a cyclonic circulation or 'mini-barge'.) Since 1998, we have watched three such sectors arise and evolve and collide with segment A (**Fig.4**). Here their history is summarised.

(A) The structured segment of STB f. oval BA, here named **STB segment A**, is always present but varies enormously in size and complexity. In 2001-02 it was a fairly short dark STB segment, but it shrank to a small cyclonic v.d.s. in early 2003.

In 2003/04, STB segment B (see below, & **Fig.6**) collided with it, making it very long again. It then shrank gradually until 2008, and was a small v.d.s. in 2009.

In 2010, the next structured sector, called the 'STB Remnant' (see below), collided with it in turn, with spectacular effects, making it very long again. It then shrank gradually again, and was a small v.d.s. in 2012.

In each cycle the average shrinkage rate has been ~1.6 deg/mth.

(B) STB sector B grew out of 'DS2', first seen in 1998 as one of 3 dark spots which already formed the typical pattern **(Fig.1A,B)**; remains of all 3 can be seen in the Cassini map [**Fig.2** & ref. 3].

DS1 was a small cyclonic v.d.s. which gradually reddened and faded. (On its f. edge, another faint feature formed in 1999/2000, called DS1b, probably at the p. edge of a small cyclonic circulation, and later had a white spot on its S edge –similar to the later 'STB Remnant', but did not develop at all until it merged with segment A in 2003.) DS2 was a variable dark grey streak, which grew into a long dark STB segment over several years. DS3 was a v.d.s. in the STZ, at least sometimes having a white core, so it was an anticyclonic dark ring, and may have become an AWO in 2000.
DS2 (segment B) gradually lengthened until ~55° long by the end of 2003 (**Fig.5):** it lengthened at a rate of 0.6 deg/mth increasing to 1.0 deg/mth.

In 2003/04, segment B collided with segment A. This collision was a notable event at the time, but since our report is no longer on our web site, it is repeated here (in Appendix 4) plus **Fig.6**. The following paragraphs briefly summarise it, and note additional consequences of the collision which we can now recognise.

> ***Summary:*** In 2003 Oct-Nov., the faint STB streak of DS1b had already merged with and enlarged STB segment A. (This may be why oval BA suddenly accelerated around Dec.1.) F. it was a white sector of STB, 27°. long in Dec. [labelled W on the images]. F. this was a dark brown spot in the STZ (labelled LBS; gradually fading), and then the long dark STB segment B. At the New Year, v-hi-res images revealed that the white sector had turned into a turbulent patch; the conversion was probably seen occurring on Dec.24. This was a short-lived state, marking the conversion of this cyclonic sector to normal dark belt. From mid-Jan. onwards, all these sectors f. BA had fused to form a long dark STB, although it was still often irregular on a small scale.
>
> ***then:*** The JUPOS charts and maps show that the Sf. extension of segment B, hitherto rather quiet, developed large numbers of dark spots emanating from the merged STB segments from Jan. onwards. Meanwhile the STB(N) p. oval BA, formerly quiet, was invaded by a new outbreak of STBn jetstream spots from late Feb. onwards. Both these strings of dark spots were no doubt consequences of the turbulence attending the collision of the STB segments.

Around the start of March, ~35° f. BA, a tiny anticyclonic ring or AWO developed on STBs, possibly derived from the former LBS. At the same time, the sector of STB between BA and this AWO became darker and possibly less turbulent; it shrank until it was a short, very dark bar in 2004 June.

(C) The 'STB Remnant'. This long-lived but always faint sector developed from a tiny cyclonic v.d.s (called dsA) which appeared in late 2002 – when it was already, intermittently, associated with a very small faint oblique cyclonic feature. It remained a v.d.s. until 2004 April, but shrank and vanished in May, leaving only faint blue-grey and white streaks, which thereafter persisted and expanded as the so-called STB Remnant **(Fig.7A,B)**. It became a familiar feature, documented in several of our reports (see 'Reports' on this web site & list in References).

By 2007, with v-hi-res images from New Horizons and HST as well as amateurs [see Fig.3, and 'Reports' 2007 no.20 (Fig.10)], it had the appearance of a slightly oblique cyclonic circulation, its periphery marked by the blue-grey streaks. The putative circulation was not demonstrated directly at the time, although HST images taken in 2007 and 2008 and 2009 might be able to do so [see examples in 'Reports' 2007 no.20, 2008 no.6 (Fig.3)]. The STB Remnant did interfere with adjacent jets, as it occasionally caused incoming spots to recirculate, e.g. from SSTBn to STBs in 2008 July ['Reports' 2008 no.6 (Fig.4); see section 5.2 below] .

There was also a smaller oblique blue-grey streak just p. the STB Remnant, first noticed in 2007. It probably developed from a tiny cyclonic v.d.s. present in 2006, like the STB Remnant itself, but it remained as a single faint streak. This streak encountered segment A in late 2009, without immediate effect.

Then the STB Remnant collided with segment A in 2010, with spectacular effects. Exceptional cyclonic shear became apparent during the process: we observed DL2 = +100 deg/mth for spots on its S edge in June (the fastest retrograding speed ever recorded on STBs), and DL2 = -110 deg/mth for two spots within its N edge in July. These and many more effects were described and illustrated in more detail in 'Reports' 2010/11 no.4 & no.8, which are not repeated in full here, but were summarised as follows.

> *[Summary, report no.4]: "*On 2010 June 17, three long-lived features in the S. Temperate domain collided: two anticyclonic circulations (oval BA and the small white oval following it), and a cyclonic circulation (the STB Remnant). The arrival of the STB Remnant apparently impelled the white oval into contact with oval BA, leading to the rapid merger of the two anticyclonic circulations. Meanwhile, on the same date, a brilliant, methane-bright white plume erupted in the STB Remnant, initiating never-before-observed fireworks in the cyclonic circulation. These events seem to be miniature versions of phenomena observed in the S. Tropical domain. The merger may have been similar to the merger of the GRS and LRS in 2008, while the outbreak in the STB Remnant is a miniature version of a SEB Revival outbreak, including intense convection at the source and rapid motion on the retrograding STBs jet. By mid-July, the STB Remnant seems to be establishing itself as a STB segment f. oval BA, but is still very turbulent."
>
> *[Summary, report no.8]:* "The South Temperate Region now contains just two segments of dark STB, since a third formation, the STB Remnant, collided with the segment f. oval BA and radically changed the region around it. Dark spots streaming Sf. from this STB segment are merging into a single dark ring in the STZ, which has become methane-bright during the mergers. Oval BA has just passed the Great Red Spot (GRS). Both STB segments are emitting exceptionally dense streams of spots in the STBn jetstream."

Thus, the striking consequences included intense outbreaks of dark spots slow-moving in the Sf. extension and also prograding on the STBn jet (but see also discussion below of the STBn jet).

(D) A new small faint oblique streak was seen in early 2008, and gradually expanded, becoming a typical dark STB sector (segment D), over 50° long in 2012 (**Fig.5)**. Segment D lengthened at a rate of 1.1 deg/mth increasing to 1.6 deg/mth. This is now colliding with segment A in early 2013 (see 'Reports' 2012/13 nos.10 & 11).

(E) Meanwhile another small v.d.s. (named DS4) appeared in 2011, in a small cyclonic faint blue patch, where there was also temporary disturbance of the SSTBn jet [ref. 2011/12 report to be posted soon]. It became remarkably dark in 2011 Nov., until 2012 Sep. Then it faded and turned white, within a faint cyclonic streak, **(Fig.7C)** & [Ref.10], just like other v.d.ss. have done [see below], and we have predicted that it will become the next STB structured sector. (If it remains faint like the STB Remnant, we will suggest naming it the 'STB Ghost'.)

Thus, the initial small cyclonic feature can be either a v.d.s. or a faint streak, which then develops. Similar features have also appeared without developing further, but all 3 of these (DS1/DS1b, 1997-2003; v.d.s., 2006; DS1, 2011/12) ended up as faint structures shortly p. the larger structured sectors. It seems that these small cyclonic features only develop into new structured sectors when there are no other major features over a wide range of longitude. But whenever an existing structured sector has migrated towards segment A, leaving a long undisturbed sector, that is where a tiny cyclonic eddy is liable to develop and initiate the next cycle.

Cyclonic dark spots turning red and fading

Several years ago we found that cyclonic dark spots (‘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” [ref.4, p.215]. One of the earliest examples recognised was a cyclonic circulation in the STB called the 'Morphing Spot', in 1995 [ref.11; see **Appendix 1**].
Since then we have noticed three further, very similar examples in the STB: DS1 in 1997-2000 (**Figs.1 & 2**), and two spots in 2011-12 named DS1 and DS4 **(Fig.7C)**. Both began as exceedingly dark small cyclonic spots (v.d.ss.), then turned to brown and rapidly faded to a “luminous pink spot”, with just a faint blue-grey streak adjacent.

5. Spots in the STBs jet and the STZ

5.1. Dark STB(S) (Sf. extensions of dark STB segments)

A dark STB segment always has a Sf. extension or ‘tail’, except for segment A when it is just a very dark oval. The STB Remnant did not have one either, so the Sf. extension apparently arises from an ‘open’ cyclonic segment but not from a closed circulation. Mostly the Sf. extension consists of amorphous dark grey spots or streaks, sometimes cohering into a continuous STB(S). Sometimes they include distinct ovals or rings – from their latitude, presumably anticyclonic circulations (see below), indicating that dark material crosses the STBs jet.

Sf. extensions can become longer and darker under two circumstances. First, the two collisions of STB segments with segment A each resulted in many spots being emitted into the Sf. extension. Secondly, when an STB segment has just passed the GRS, the Sf. extension sometimes elongates so that its f. end remains roughly south or Sf. of the GRS for some months – as observed in spring, 2002; spring, 2005; and autumn, 2011.

Whereas whole structured sectors move with the STC (DL2 = -16.7 [+/-1] deg/mth) , the dark spots in these tails are usually slower-moving, having DL2 ~ -4 to +12 deg/mth, although they only rarely approach the speed of the STBs jet as measured by spacecraft (+20 to +42 deg/mth: Table 1). However there have been notable variations from year to year. The typical speeds since 2001 can be summarised as follows, from our preliminary results. (In the next section, more precise JUPOS measurements will be presented.)

2001-2003: DL2 = -1 to -8 deg/mth, f. segments A and B.
2003/04: A well-defined series of spots with +2 to -4 deg/mth f. segment B; but from 2004 March onwards, after segments A and B merged, speeds of ~+12 deg/mth were also recorded.

2005-2007: Remarkable rapidly retrograding speeds appeared in 2005, DL2 up to +30 deg/mth, first discovered at the time by K. Horikawa analysing observations for the ALPO-Japan. They were all in the long tail of the merged STB segments. These speeds were maintained here in 2006 (4 with +31 to +37 deg/mth, one with +43!) and 2007 (4 with +26 to +27 deg/mth, one with +44!). There were also many spots with 0 to +8 deg/mth (2005, 2006), -8 to +19 deg/mth (2007), on a well-defined gradient just south of the retrograding jet.

2008: A regular series of spots with +17 deg/mth, indicating a partial return to normal (although one exceptional small spot with +37 was recorded elsewhere in the STZ).

2009 to 2012: Some spots with +6 to +14 deg/mth, and some with ~-1 to -15 deg/mth, on a well-defined gradient just south of the retrograding jet.

It seems likely that the outbreak of spots in the STBs jetstream, from 2005 to 2007, was a consequence of the collision of STB segments in 2003/04. The rapidly retrograding spots were all in the long tail of the merged dark segments, and were at 31.7 to 32.5ºS, the latitude of the jet peak where very few spots had previously been recorded. However, previous and subsequent spots in this latitude range had much less extreme speeds, so there was a very significant acceleration of the drift rate in 2005-2007, as we show below.

It is also notable that only the tail f. segment A shows spots in this latitude range. The tails f. segments B and D have not shown any, except for a few f. segment D in 2010 (1) and 2011 (2).

5.2. The Zonal Drift Profile of the STZ and STBs jet

We analysed the ZDP for all the dark spots recorded during these years in the Sf. extensions of the STB dark segments **(Fig.8 & Table 2).** We conclude:

1) Although these are almost all dark spots, most of them are in the anticyclonic latitudes of the STZ, while the remainder are close to the retrograde jet latitude (~32ºS). There are only a few in the cyclonic STB latitudes.

2) Many though not all of the spots migrated southward during their lives, presumably following the trend of the STB(S) 'tail' as they drifted towards its Sf. end. Most of these either changed their speed and latitude in accordance with the ZWP, or showed no change in speed as they crossed the retrograde jet peak.

3) There is general agreement with the Cassini ZWP, except:

4) Variability at the retrograde jet latitude (~32ºS): the spots' ZDP here is usually blunter than the ZWP (as in other domains) (DL2 ~ -5 to +15 deg/mth); but in 2005-2007, the spots f. segment A showed the full jet speed (+26 to +44 deg/mth), with intermediate speeds in 2008 as it returned to normal. Perhaps this was a long-lasting effect of the STB collision in 2003/04?

5) The ZDP Sf. segment C (the STB Remnant) was displaced southwards or slower than normal, from 2004 to 2007 – including the tracks of spots which recirculated from SSTBn to STBs (see below). This anomaly also returned to normal in 2008. Perhaps this distorted profile was associated with the STB Remnant, which may have interrupted the zonal pattern across the STZ?

6) Several spots recirculated from the SSTBn prograding jet to become slow-moving in the STZ or retrograding in the STBs jet.

This mainly happened at the Sf. end of the STB Remnant (7 spots, including some very small ones not included in the general analysis, 2004-2008). No SSTBn jet spots passed the STB Remnant unimpeded (some disappeared while nearing or reaching it), and we found only 3 examples of a slow-moving spot appearing at the Sf. end of STB Remnant which had not come from the SSTBn jet.
Similar recirculations from the SSTBn jet occurred rarely elsewhere: Sf. STB segment A (4 spots) and alongside undisturbed STB (5 spots) (2004-2011).

Points (5) and (6) suggest that the STB Remnant altered the ZWP f. it, such that the gradient across the STZ was displaced southwards, and any SSTBn jetstream spots prograding along here were recirculated or extinguished. However, any change of the ZWP must have been quite local as no difference was seen between long sectors p. and f. the STB Remnant in data from New Horizons in 2007 (see section 7.3 below with **Fig.18**).

The observations that dark spots near the STBs jet can wander in latitude (some move southwards across the jet), and are mostly amorphous patches with no obvious vorticity, are consistent with the emerging picture of retrograding jets, which are not such distinct dynamical boundaries as the prograde jets (see **Appendix 2**).

In section 7.3 below, we will examine the STBs retrograding jet from spacecraft data and show evidence that it is sometimes faster in structured sectors. Spacecraft ZWPs will be compared with our ground-based spot tracking, showing that the peak drift rates we have reported in 2005-2007 are the same as the peak wind speed in undisturbed sectors.

5.3. Anticyclonic ovals in the STZ

Apart from oval BA, there have been no large anticyclonic circulations during these 12 years. There is usually a small AWO Sf. oval BA, but it is not very long-lived; at least three have succeeded each other since 2000. A few appear elsewhere but these are all very small. They always appear in the Sf. extension of a dark STB segment, often at its f. end, and the birth of a new one observed in 2010 may be a good example [see below and ref. report above].

Tracking and identification of these AWOs/rings is limited by resolution. Some tiny ones were resolved and tracked in recent years that would have been missed in earlier years. Six such spots have been clearly tracked, as follows.

(1) 1998-2001: DS3 in 1998 (Sf. DS2 which became STB segment B); v.d.s. with white core in 1999-2000; probably became an AWO in late 2000. (**Fig.1B**) (Fate unknown.)

(2) 2000-03: AWO f. BA in 2000-03. (Fate unknown during solar conjunction.)

(3) 2002-04: AWO appeared in 2002 near f. end of long Sf. extension from STB segment B. It drifted away from segment B until mid-2004 and was then lost.

(4) 2003 –(?)-> 2004-07 –(?)-> 2009-10:
AWO appeared in the long disturbed sector f. BA in early 2004 (possibly from Little Brown Spot seen in autumn 2003 between converging STB segments A and B [see above]?). It remained ~30^{o} f. BA [all distances are between centres] until 2007, then receded to ~50 ^{o} f. BA. It may have been the same spot in 2008 which was a v.d.s./ring, fixing the f. end of the Sf. extension, and then may have become the tiny AWO $\leq$20^{o} f. BA in 2009. This AWO met its end during the collision with the STB Remnant in 2010, which propelled it into rapid merger with BA [ref. 'Reports' 2010/11 no.4, cited above].

(5) 2010-11: AWO formed in 2010 in the aftermath of the collision between segment A and the STB Remnant, when retrograding dark spots in the invigorated Sf. extension merged [ref. 'Reports' 2010/11 no.8; see above]; the merging spot suddenly became methane-bright and persisted as an AWO until early 2011. (Fate unknown during solar conjunction.)

(6) 2010-12: Tiny dark ring or AWO appeared in 2010 at f. end of Sf. extension of STB segment D. It had variable drift relative to segment D, and persisted as a tiny AWO into 2012. (This one was so small that it would not have been tracked in earlier years.)

Note that numbers 1,4,5, were probable examples where a dark anticyclonic spot developed a white core and became an AWO. Of these 6 spots, most lasted for 2-3 years, but no.4, if genuinely identified between apparitions, lasted 7 years.

6. Oval BA

The great anticyclonic oval BA formed when 3 pre-existing large AWOs underwent successive mergers in 1998 and 2000 [refs.2,8,9]. Until 2005 it was dull white. In 2005 Dec. it became reddish, a colour which intensified in early 2006, and it has retained some reddish colour since, always in an annulus with a white core of variable size. Views of BA in cylindrical maps (from Fig.3) are compiled in **Fig.9.**

6.1. Variations of drift rate

The drift rate of oval BA in longitude since 2001 is shown in **Figs.4 & 10**, and listed in Table 3. There are obvious variations. For example in 2011 Aug. the speed changed from DL2 = -19 to -11 deg/mth within only ~10 days. Fast or slow speeds can be maintained for a year or more, but there can also be more frequent changes of speed. These speed changes are coupled to latitude changes, as described below.

Major changes in drift rate:
Some speed changes appear to be related to passages past the GRS. Oval BA is usually drifting slowly as it approaches the GRS and always drifting rapidly as it departs; sometimes there is a sudden acceleration just before or during the conjunction.

But major speed changes also occur remote from the GRS. The most notable rapid speed changes, between tracks lasting more than 2 months with a change of more than 2.0 deg/mth (Table 3), were as follows.

Decel., 2002 (during solar conjunction; soon after passing GRS).
Accel., 2003 Nov. -- This coincided with the impact of small cyclonic structure DS1b.
This led into the impact of the much larger STB segment B,
although there was no further change in speed of BA.
Accel., mid 2004 (just before passing GRS, end of apparition).
Decel., late 2004 (start of apparition).
Accel., 2006 June (just before passing GRS).
Decel., 2008 Sep. (soon after passing GRS).
Accel., 2010 Sep. -- This coincided with conjunction with the GRS, but also occurred 3 months
after the remarkable impact of the cyclonic 'STB Remnant'. (See **Fig.12.**)
Decel., 2011 Sep.

The two great accelerations with longest-lasting effects coincided approximately with the two great collisions, as shown in **Fig.4**, when a structured sector of the STB caught up with the short STB segment f. BA, called segment A. Although the timecourse was not identical in the two cases, it seems very likely that these collisions were what impelled oval BA to a faster drift and higher latitude.

The decelerations did not coincide with any obvious, sudden external events. However, all four of them can be attributed to shrinkage and quiescence of the STB segment A – i.e., the opposite phase of its cycle. The three greatest decelerations occurred just as this STB segment was completing its contraction in length and was turning into a dark cyclonic 'barge'. The other deceleration, in 2004, happened when the turbulence of STB segment A due to the 2003/04 impact had diminished and a distinct dark segment had formed and shrunk **(Fig.6D)** – and as the deceleration occurred during solar conjunction, segment A could have formed a barge unobserved at that time.

(During the deceleration in 2011 Aug/Sep, there was no distinct change in the appearance of dark segment A: it was a small dark bar throughout (see report to be posted soon). Turbulence had apparently ended in July. So the deceleration may be a delayed response, or may depend on dynamics below our threshold of resolution.)

The fact that most decelerations have occurred soon after passing the GRS could reflect changes in the STB segment A induced by those GRS passages, as well as reversion from the acceleration induced by GRS conjunction itself.

Discussion:

We propose that the speed changes of oval BA are principally due to changes in the STB segment on its f. edge, segment A. Accelerations occur most strikingly due to the impact of structured STB sectors onto segment A, whereas decelerations occur when segment A resolves (after prolonged shrinkage) from a turbulent state to a smaller, quiescent barge. The turbulent state, with vigorous small-scale convection and generation of spots on the STBn jet, may exert a force on oval BA, which is relieved when it converts to a quiescent cyclonic circulation. The word 'force' is used in a colloquial sense, and these hypotheses will need to be developed properly in terms of atmospheric physics. In section 6.5 (below) we note that the turbulent rifted SEB f. the GRS may exert a similar force on the GRS, relieved when the SEB becomes quiescent.

The suddenness of the speed changes suggests that a threshold exists, perhaps for the activity in STB segment A to exert force on BA, or perhaps for BA to respond to it. Changes in speed and latitude are coupled (see below), and it is not clear which is primary, since the eastward force can be imagined either to accelerate the oval directly, or to act like a wedge pushing it southwards into a faster zonal flow.

The exact timing of these changes may also be influenced by the passages past the GRS, since several of the events listed above can be attributed either to the STB events or to the GRS passages (as in **Fig.12**), and these may well have acted synergistically. The effect on oval BA of passing the GRS can be explained either by the STBn jet being slightly deflected southward by the GRS, thus accelerating the whole S.Temp. domain; or by oval BA itself being slightly deflected southward into the faster latitude of the STZ.

Likewise the earlier great AWOs generally showed accelerations when passing the GRS [ref.1, p.226]. Those passages also sometimes produced larger structural effects in the STB, inducing STB Fades (recirculations), and ultimately were implicated in the two successive mergers in 1998 and 2000 that created oval BA [refs.2,8,9].

Short-term changes in drift rate:
In 2007, the speed of oval BA showed remarkable oscillations, with period ~104 days, as observed through 3 cycles **(Fig.10B)**. Indeed, within the scatter of the data, the period and phase were indistinguishable from the 90-day oscillation of the GRS, which was proceeding during this time as always. In other years, there was no evidence of such regular oscillations.

One can speculate that oval BA was induced to oscillate due to passing the S. Tropical Disturbance (STrD-1) in 2007 Feb., or possibly the GRS in the previous apparition, just as one AWO in the SSTZ is induced to oscillate on passing oval BA [report to be posted soon]. However, the effect has not been seen again.

The motion and form of oval BA from 2000 to 2008 were also analysed by Garcia-Melendo et al. [ref.12] from the same sets of amateur images, and their trends in drift rate and latitude agree with ours, although their latitude values are ~0.5º higher than ours, suggesting a systematic difference in definition of the oval centre or of the limb.
In addition to the major speed changes, they found evidence for an oscillation in speed with a period of ~159 days. This would encompass the minor changes that we see from 2004 to 2007, but they do not appear to have a strict periodicity, and speed variations from 2007 onwards do not seem to have followed this period.
They found no consistent changes in speed upon passing the GRS . Although we note that the speed is always faster either during or just after the passage, we agree that there is not a consistent change at the time of conjunction, and the duration of any change is very variable. The GRS is probably just one of multiple influences on the motion, to which oval BA responds discontinuously and only when a certain threshold for change is reached.

6.2. Variations of latitude and the zonal drift profile

Two interesting questions arise about the latitude of oval BA: whether it is related to the drift rate (responding to the ZWP), and whether it has changed over time since the oval formed. We have therefore analysed the JUPOS measurements, and can answer both questions in the affirmative. We already showed how anticyclonic ovals of different sizes in the NNTZ have different ZDPs, probably due to the way the larger ovals distort the surrounding ZWP [ref.7]. Here we show the same effect for oval BA, as a function of shrinkage with time.

We calculated the drift rate and latitude for each track segment that had a stable drift rate for at least 2 months (Table 3, & **Fig.11A**).

From 2001 to 2007, the points lay close to a single line (ZDP), at lower latitude than the spacecraft ZWP and with a shallower gradient. This is also consistent with the results of [ref.12], which found a progressive increase in latitude from 2000 to 2007, related to the speed. Starting in 2008, however, oval BA has been further south than this line. In fact, while it still follows a ZDP with similar gradient over a year or two, the ZDP has been shifting progressively further south at ~0.1º/year. Also, the gradient may be becoming steeper (though any such difference is within the uncertainties), gradually approaching the spacecraft ZWP **(Fig.11A)**.
As a control, the JUPOS latitudes for the SSTB AWOs at 40.5ºS showed no change over the same interval [data not shown], indicating that the changes for oval BA were significant.

The only discordant data point was from early 2004, just after the impact of a STB segment, which accelerated oval BA but also shifted it disproportionately to the south. (This may have been due to dark material filling in the white collar; see below.) Hi-res examples of the speed-vs-latitude relationship can be shown for 2010 **(Fig.12)** and 2011/12 [in our apparition report, to be posted soon].

The ZDP for oval BA from 2001 to 2007 was offset from the ZWP just like the ZDPs for other large ovals, such as NN-LRS-1 in the NNTZ [ref.7]. This appears to be because these largest anticyclonic ovals are wider than the anticyclonic zone and distort the adjacent retrograding jet [ref.7]. After 2007, the increasingly southerly ZDPs of oval BA are very similar to the parallel ZDPs of different-sized anticyclonic ovals in the NNTZ [ref.7]. The progressive shift of the ZDP for oval BA suggests that the oval is shrinking, and thus distorting the ZWP less, since 2007. In section 6.3 (below), we will show that this is the case.

It is interesting to compare these results with the speed-vs-latitude relationship for the three previous long-lived ovals [ref.13, reproduced in ref.1, p.227], which showed good correlation overall, but increased scatter in the 1980s, when the ovals became quite small. In the earlier work, the possibility that the ZDP shifted over time was not considered. Therefore we have re-plotted the data, with new points for the 1980s and 1990s segregated by the size of the ovals **(Fig.11B).** Indeed, the data since 1950 are better fitted by ZDPs which shifted southwards, and closer to the modern ZWP, as the ovals shrank. These ZDPs show excellent agreement with those derived for oval BA (**Fig.11C)**. From 1950-1978, the three ovals were large and followed a ZDP shallower than BA has ever shown. From 1979-1989, when the ovals were 8.5 to 10.5° long, they followed the same ZDP as BA in 2008-09, when it was 9-11° long. From 1984-1996, when the ovals were 7-8° long, the points were consistent with the ZDP of BA in 2012, when it was 7° long.

From 1940-1945, the three ‘proto-ovals’ were long sectors of STZ that had not yet assumed oval form, and they drifted very fast but fitted onto the Cassini ZWP. This is to be expected in this early stage of their evolution, whether or not they had developed their full anticyclonic circulation by then [see section 8 below].

6.3. Shape and size of oval BA

The shape and size of oval BA have been evolving since it formed by merger of two large AWOs in 2000. Amateur images in 2000-2002 showed an outline that was somewhat triangular, with its northern part extending right across the STB. It gradually became more oval during 2003, but has still retained some asymmetry even up to 2011 **(Fig.9)**. When the red colour appeared in 2005-06, it was an orange annulus which often did not completely fill the outline of the oval. **(Fig.9).**

Caution is needed in interpreting ground-based images of oval BA, not only because of limited resolution, but also because the visible oval may include a white collar that lies outside the circulation itself (as has been demonstrated by spacecraft imaging). The visible asymmetry, particularly in the early years, also suggests that the size and latitude of the visible oval may differ from those of the circulation itself.

Spacecraft images resolve the circulation pattern and the surrounding halo, and those from 2000 to 2007 have been repeatedly analysed by professional groups [**Appendix 3**]. The best images were obtained by Cassini in 2000/01, by HST in 2006 April, and by New Horizons in 2007 Feb. The reports cited in Appendix 3 are consistent in regard to the size and shape of oval BA, as defined by the contour of maximum wind speed. All agree that in 2000/01, BA was a ‘triangular oval' not only in its visible outline but in its flow pattern, which had a northern extension across the STB. By 2006 and 2007, BA was closer to a true oval and its northern edge had moved 0.8º south. In contrast the dynamical centre and south edge had shifted just 0.4º south – which was attributable to the faster drift rate in 2006-07 – so the maximum-speed contour had narrowed from 5.4º to 5.0º in width.

This contour approximately coincides with the outer edge of the orange annulus, and the speed falls off very rapidly outside it; so the orange annulus marks the true dynamical oval. Perhaps surprisingly, it does not differ systematically from the visible oval (Table 3) in shape or in central latitude, although the visible oval is larger. In the following account, therefore, we continue to refer to the visible outline of the entire oval including any white collar. Although spacecraft images have not yet been analysed from 2008 onwards, BA has been a more symmetrical, well-defined oval during these years, so it seems likely that our conclusions below are still valid for the circulation itself as well as the visible oval.

The length of the visible oval in longitude is listed in **Table 3** and plotted in **Fig.13A.**
From 2000 to 2007, there was no overall change in the length of the visible white oval, as measured from:
--amateur images, white light: average 10.8º (+/-1.1º) [JUPOS, this report];
--amateur images, red/IR light: average 10.6º (+/-0.8º) [JUPOS, not shown];
--amateur images: average 10.5º (+/-1.5º) [ref.12];
--spacecraft images: average 9.5º (+/-0.5º) [ref.12];
--contour of maximum wind speed: average 6.3º [ref.14].
However, from 2008 onwards the visible length has been diminishing irregularly **(Table 3 & Fig.13A).**

Discussion:
The length of oval BA since 2007 has been well correlated with its latitude **(Fig.13B)** – as expected on our hypothesis that the oval's position has shifted southwards as it has shrunk (see above) The length is not correlated with the drift rate (data not shown), which is also consistent with our hypothesis.

The oval was anomalously short in 2003/04 and 2010, during the impacts of STB segments f. BA. At these times it also acquired a very dark grey rim, probably derived from the incoming dark STB segment. At these times it also suddenly accelerated and shifted south (see above) -- obeying its ZDP in 2010, but with a disproportionately large southward shift in 2003/04. These changes can all be explained by dark material which filled in the usual white collar around the circulation. In 2010, this caused the apparent size of the oval to shrink but did not affect its apparent latitude. In 2003/04, however, the oval retained more of its initial asymmetry, so the collar may have been broader on the north than on the south, so when the collar darkened it caused an apparent southward shift.

The width of the oval in latitude has also changed, along with its shape. As noted above, the width diminished from 2000 to 2007 as measured from spacecraft images. Since then, the width has not been directly measured, but we adopt the working hypothesis that the width and length have diminished together.

These results all support our hypothesis that shrinkage of BA was responsible for the changes in the ZDP. From 2000 to 2007, the size did not change and the ZDP did not change, so the change in shape and width did not affect the ZDP: BA consistently behaved as a large oval, deflecting the retrograde jet. However, from 2008 onwards, it has shrunk in length and the ZDP has gradually shifted south towards the spacecraft ZWP, implying that it has shrunk in width as well and thus distorts the retrograde jet less -- following the same relationship that we found for the NNTZ ovals.

6.4. The colour of oval BA

Reddish colour was recorded in BA for the first time in 2005 Dec., just after solar conjunction, and intensified until 2006 April [ref.15], forming a strongly orange annulus which persisted thereafter, fading very gradually from 2007 to 2009. During most of 2009 it was merely pale fawn, the same colour as the surroundings. But it regained some orange colour during 2009 Dec. and 2010 Jan., and was strongly orange throughout the 2010/11 apparition. In 2011/12 the colour was weaker – pale ochre. Then by mid-2012 it was strongly orange again, and in late 2012, probably stronger than ever. These changes are summarised in Table 4.

These colour changes do not correlate with any other parameter that we have recorded for oval BA: not with its speed, nor latitude, nor length, nor with its conjunctions with the GRS, nor with impacts of STB segments, nor with the presence of a dark rim around it. When the red colour first appeared in 2005/06, and reappeared quite rapidly in 2009/10 and in 2012, there were no other special phenomena in the vicinity, as far as we can tell.

We conclude that the colour changes have an internal origin – just like those of NN-LRS-1, the similar oval in the NNTZ, whose redness also fluctuates with no regard to other phenomena.

6.5. Comparisons between oval BA and the GRS

Oval BA and the GRS are the two largest anticyclonic ovals on the planet, and now have similar colour. Do the phenomena reported above suggest any additional similarities or differences between them?

It seems likely that the drift rate of each oval responds similarly to changes in the cyclonic turbulent sector f. it. The dark turbulent STB segment A is homologous to the SEB f. the GRS, which has large-scale convection and turbulence seen as bright ‘rifting’. Oval BA decelerates when segment A becomes small and quiescent; likewise, the GRS decelerates when the SEB becomes quiescent, at the start of a SEB Fade [ref. ‘Reports; 2010/11 no.8]. So it is plausible that in each case, high drift rate is maintained by pressure from the turbulent region f. the oval, and deceleration occurs when this turbulence ceases.

Is there any similarity in the colour variations of the GRS and oval BA? It is well known that the GRS becomes very reddish during an SEB Fade (when its drift rate decelerates), and much paler after an SEB Revival (when it drifts faster again); so the redness also correlates with deceleration. However, this is not the case for oval BA. This suggests that the reddening of the GRS during SEB Fades is not due directly to the lack of convection in the SEB, nor to the concurrent change in drift rate. Instead, it has long been attributed to the lack of incoming spots from the other side, from the retrograding SEBs jetstream, which visibly disrupt the red cloud cover when they enter the GRS. Oval BA is not subjected to any comparable barrage of retrograding spots, and the variations in its red colour appear to be random and internally generated.

7. STBn jet : the profile varies with longitude

The STBn jet has been active with at least some small dark spots in every apparition since 2004 **(Fig.14)**. Before 2004 the record does not extend to such small spots, so careful study of images and maps will be needed to provide any rigorous assessment of activity levels; but it is clear that the number of STBn jetstream spots did increase greatly in 1999 (the first outbreak since 1994), and in 2003/04 and again in 2010, as will be discussed below.

The STBn jetstream spots mostly appear just Np. one of the structured sectors, either at oval BA or at a dark STB segment. In 2007, in addition to the spots intrinsic to the STBn, there were also many recirculated from the SEB Revival via a South Tropical Disturbance, which mostly ended up at 26-27ºS, but some remained below 26ºS and so are not included in Fig.16 and Table 5 [ref. 'Reports' 2007 no.20].

Table 5 lists the speeds recorded for STBn jetstream spots. (This is a preliminary listing, as the JUPOS data have not yet been fully analysed for each apparition, but the results are unlikely to change substantially.) The speeds and latitudes show considerable range and variability. Mean speeds are particularly low at the start of a new major outbreak (DL2 ~ -76 deg/mth: 1999/2000, 2003/04, 2010). Peak speeds are often around -95 but sometimes reach -110 to -113 deg/mth, although never quite as fast as most spacecraft values (Table 1).

Most other prograde jets have a sharp peak in spacecraft ZWPs, and where dark jetstream spots can be tracked, they are typically anticyclonic vortices, rolling along the low-latitude (anticyclonic) side of the jet peak (Appendix 2). However, the STBn jet often has an unusually broad peak in spacecraft ZWPs, often double (Table 1 & refs. therein). In the Voyager and New Horizons ZWPs, it was double with almost equal sub-peaks at ~26-27 and 29ºS; whereas in the HST and Cassini ZWPs it had a single major peak at 26-27ºS, with a minor 'shoulder' at ~29ºS.

Here we show that STBn jetstream spots often drift northwards during their life without change of speed, and that there are systematic longitudinal variations in the profile of the jet peak, related to the different sectors in the STB, which reconcile the previous ZWPs. We consider: (1) the course of the tenuous STB(N), (2) the tracks of jetstream spots within it, and (3) the zonal wind profile across it as established by spacecraft.

7.1. Latitude of the visible STB(N)

As can be seen on the best maps of the planet **(Fig.3)**, the dark STB segments are altogether further south than the tenuous STB(N) in undisturbed sectors. This STB(N) emerges from the Np. corner of a dark segment, and tilts north over ~10-50º longitude in the p. direction. Further p., the STB(N) becomes increasingly faint and narrow, but its N edge remains fixed in latitude; and thus it extends N of the next dark STB segment.

This tilt is documented by measurements of the STB(N) latitudes in 2006 and 2010 **(Fig.15)**. This confirms the tenuous STB(N) does trend north for ~80-180º p. oval BA.

7.2. Latitude of STBn jetstream spots

Measurements in two recent years show that the spots appear at a range of latitiudes within the broad STBn jet, and that many of them (though not all) drift northwards within the jet during their lives **(Figs.16 & 17).**

In autumn, 2010, the STBn had an unprecedented high density of dark jetstream spots all around the planet (Fig.3). Preceding oval BA, this was an intense outbreak triggered by the impact of the STB Remnant (see above). However, there was already an equally high density of spots in the other sector of the jet, p. STB segment D, with no obvious cause. It may have been connected with the concurrent fading of the SEB. Before the era of modern imaging, STBn jetstream spots were only observed in two circumstances [ref.1, p. 215]: either recirculated from a S.Tropical Disturbance, as in 2007, or arising during a SEB Fade, as in 2010. Thus the SEB Fade may have dynamical consequences across the S.Tropical Zone.

JUPOS measurements in 2010 (Fig. 16A) showed that many of the numerous STBn jetstream spots drifted steadily northwards during their lives; most of them over a span of 120º longitude, (drifting from ~28-29ºS to ~27-28ºS); and one over a span of 270 deg. longitude, (from 28.7ºS to 26.4ºS). They almost all disappeared on reaching the GRS where there was also a dark STB segment.

The map in Fig.3 provides a complementary ‘snapshot’ view of these spots, confirming that they progressively declined in latitude from each of the 2 sources. This map suggests that the spots shifted N in two stages, first some tens of degrees p. the source, and then again as they came alongside the next STB dark segment (including its Sf. extension). Tracking by JUPOS, however, showed that individual spots exhibited steady northwards drifts, although there was significant variation in their latitudes at a given longitude.

In summer, 2011, small dark spots in the STBn jetstream were arising ~40º p. oval BA and again disappearing at the GRS (alongside the f. extension of a long STB dark segment). Again, some of them (5/19 spots) drifted north during their lifetimes without change of speed (Fig.17A). These 5 spots were among 9 spots which appeared to define the jet peak (Fig.17B), with mean DL2 = -98.6 (+/-2.8) deg/mth, mean lat.27.5 (+/-0.2)ºS; but the northward drift implies that this jet peak actually had constant speed from 28.0 to 26.8ºS.

The speed-vs-latitude plots for these spots (Figs.16B, 17B) show distinct gradients, but these are also anomalous in two respects. First, the speed of the spots was much faster in 2011 than 2010: the ZDPs are offset by ~17 deg/mth. (It may be relevant that the 2010 spots were generally bigger and more prominent.) Secondly, rather than the typical anticyclonic gradient, these spots followed a weakly cyclonic gradient and ran on the cyclonic (south) side of the Cassini jet peak. However, there are several reasons for suspecting that these were not really cyclonic spots. In ZWPs from other spacecraft, the STBn jet peak was very broad or double, from ~26.5 to 29 S, so these spots in 2010 and 2011 may actually run within the peak. All the JUPOS results suggest that the jet as a whole shows a systematic northwards trend, but also that individual spots have a tendency to drift northwards within the broad jet peak. This will be discussed further below.

7.3. Zonal wind profiles in different sectors

Published ZWPs from spacecraft (Table 1) were all globally averaged. Here, we report ZWPs from two spacecraft data sets within 4 longitude sectors representing different sectors of the STB. Due to the high resolution of spacecraft images, these can detect wind speeds from subtle cloud features even where there are no distinct spots to track. This can also be achieved, albeit with less precision, from the best recent amateur images, and we show that ZWPs from amateur images reach the same conclusion.

(a) New Horizons ZWPs, 2007 Jan. (by Grischa Hahn) **(Fig.18)**

The images were from New Horizons [ref.18], and the full ZWPs have been posted [ref.19].
Both sub-peaks, at ~29ºS and 26ºS, are present in most of the profiles, but their relative speeds and latitudes are variable (contrasting with the constancy of the SSTBn jet further south).
Sector 4, with the dark STB segment, has the fastest sub-peak at 29ºS (u = +44 m/s), which must represent the N edge of the dark STB segment; and the slowest more northerly sub-peak, at 25ºS (u = 24 m/s), which may represent the extremity of the STB(N) from higher longitudes. Sectors 1 and 2, in undisturbed STB (and perhaps sector 3 although there were fewer valid data here), agree quite well with each other, with u ~ +39 m/s in the 29ºS sub-peak and u ~ 28-34 m/s in the sub-peak or shoulder at 26ºS. So the dark STB segment has a very different profile from the undisturbed sector, but there is no clear change in ZWP along the undisturbed sector, except where the northern sub-peak is deflected north past the next dark STB segment. (Likewise the STBs jet is constant in sectors 1,2,3, but is more rapidly retrograding along the dark STB segment in sector 4.)

(b) HST ZWPs, 2012 Sep. (by Marco Vedovato) **(Fig.19)**

The images were from HST [ref.20], and the full ZWPs have been posted [ref.21].
In this data set, two undisturbed sectors (1,2) -- and a more complex sector (3) which includes oval BA passing the GRS -- all have just one sharp peak at 26.2 to 26.9ºS, with much the same speed (u = 37.4 to 42.2 m/s). In contrast, sector (4) occupied by the single long dark STB segment displays a broad profile with the sub-peaks at 26ºS (47.7 m/s) and 29ºS (45.4 m/s). (Also, in this sector the STBs jet is more rapidly retrograding, in agreement with the NH result.)

These HST profiles differ significantly from the NH profiles, implying that the jet profile is genuinely variable. The northern sub-peak is faster at all longitudes in the HST data, while in the undisturbed sectors the southern sub-peak is absent in the HST data but strong in the NH data. Consistent features are that the northern sub-peak is strong throughout the undisturbed sectors but does not shift progressively northwards through them; and that the southern sub-peak is much stronger in the sector with the STB dark segment (as is the retrograding STBs jet).

(c) Amateur ZWPs, 2012 Sep-Dec. (by Grischa Hahn). **(Fig.20)**

Also in 2012, amateur data confirmed the HST result over a longer time-span. ZWPs from 3 longitude ranges on 3 different dates were published in our report [ref. 22], and **Fig.20** is an excerpt from these data showing the profile of the STBn jet. It confirms the previous spacecraft results very well. Two sectors of STBn have just one sharp peak at 27 S; the third sector has a broad jet with sub-peaks at 26 and 29 S, and this is the sector which contains the STB dark segment.

Finally, there is confirmation of these results from a pair of HST images in 2005 analysed by Hueso et al.[ref.23]. ZWPs obtained just p. and f. oval BA showed contrasting profiles of the STBn jet. In the undisturbed sector just p. BA, there was a sharp peak at 26ºS, whereas in the turbulent STB segment just f. BA, there was a broad peak from 26 to 28.5ºS, in close agreement with the other sectoral ZWPs above.

To compare the three sets of ZWPs directly, **Table 6** presents the peak speeds of the jets from **Figs.18-20.** This updates Table 1, which showed global averages for the jet peaks, by showing averages for structured and undisturbed sectors separately. This confirms that the STBs and STBn jets show substantial variations between the sectors and between dates, in contrast to the SSTBn jet which shows consistent values across all the data sets [& see Appendix 2].

The results are summarised in **Fig.21**, which updates **Fig.2** to show the actual relative speeds of the jets in the different sectors.

Table 6 also shows the peak speeds of these jets as assessed from JUPOS spot tracking, as presented in this report, taking either the fastest spot observed in each time period, or the average of a group which seemed to represent the jet peak. For all 3 jets (SSTBn, STBs, STBn), the peak speeds obtained from JUPOS tracking are within the range of peak speeds obtained in ZWPs, suggesting that the jet peak was indeed recorded by spot tracking in some years (though not in others). We should refrain from making precise comparisons, because the dates and sectors in which spots were tracked were not those in which ZWPs were obtained. The ZWP may have been different in years when there were plenty of spots to track.

We conclude that the STB dark segment is flanked by a strong STBn jet at 29°S (as well as a strong STBs jet at 32°S). In contrast, the undisturbed sectors have a strong STBn sub-peak at ~26-27°S, which corresponds to the tenuous STB(N) north edge, with or without a variable extension of the sub-peak at ~29°S. (They also tend to have a weaker STBs jet.) Combinations of these patterns can account for all previously published spacecraft profiles.

If these results also apply in the presence of dark jetstream spots, many of which drift from ~28-29°S to ~27°S, these spots must be drifting between the two sub-peaks of the jet. They are generated near the southern sub-peak, then drift down to the northern sub-peak but do not cross it.

These results have revealed an unusual case where a prograde jet’s profile varies systematically with longitude. The only previous case of such variation is the SEBn jet in relation to the S. Equatorial Disturbance [ref.24]. However, as it becomes possible to analyse wind speeds in ever finer detail, we may find more cases where the general assumption of uniform jet properties breaks down.

8. Discussion: The past and future of the South Temperate domain

Since the three long-lived white ovals merged to leave just one anticyclonic oval, BA, and we have shown evidence that oval BA is shrinking in turn, it is natural to wonder whether a new set of large AWOs will soon arise to replace them – as we have been expecting for several years. Throughout the observed history, the S. Temperate domain has always been divided into between 2 and 4 sectors by large AWOs or other structured segments, suggesting that there is a tendency for instabilities to form a periodic pattern with wave-number 2 to 4 around the planet [ref. 1]. In recent years, this pattern has manifested by the repeated appearance of a new cyclonic structured sector to replace the previous one as it drifts eastward towards oval BA. But can we expect large new anticyclonic structures to arise as well?

The previous set of three large AWOs arose around 1940, as long white sectors of the STZ (‘proto-ovals’), separated by darker sectors of STZ or broader STB (‘inter-ovals’) [ref. 1 & refs. therein]. We suggested [ref.13] that these inter-ovals were structures like a S. Tropical Disturbance which reconnected the jets across the STZ at each end, creating the anticyclonic circulations. But we also noted that the oval form was not apparent in the early years, and there was internal detail within each of the proto-ovals, including a distinct white oval in the p. end of each of them in 1943-1945. The proto-ovals did not develop full oval form until ~1948-1950. Therefore, it is possible that they did not have complete anticyclonic circulations until then either.

In view of the recent observations, it seems possible that the dark inter-ovals in the 1940s were actually structured STB segments like those in the 2000s, which produced discontinuities in the jets, but perhaps not actual recirculation of them. The STZ alongside a dark STB segment is narrowed or darkened to an extent that would make it appear occluded to a visual observer. The discovery that the STB Remnant induced recirculation of the few SSTBn jetstream spots that approached it suggests that these segments do have the potential to induce systematic anticyclonic circulation within the STZ.

The present situation is not the same as around 1940. Not only was there no large AWO at that time, but the STB at most longitudes was not just a tenuous STB(N) as today; it occupied most or all of its canonical width between the jets. Also, the inter-ovals drifted exceptionally fast , whereas today's STB structured segments still drift with the S. Temperate Current. (They have a rather constant speed at the upper end of the historical STC range.) No large anticyclonic circulations have developed, neither as reconnections of the jets (individual small spots occasionally recirculate, e.g. at the STB Remnant, but there have been no sustained recirculation patterns), nor as distinct white ovals (white areas are sometimes seen near the structured segments, but they are neither methane-bright nor persistent).

We suggest the following scenario. At present, oval BA is large enough to block the faster drift of the other structured STB segments, and therefore they only last for a few years, not long enough for anticyclonic circulation to develop between them. In the next few years, oval BA will shrink so much that it no longer controls the dynamics of the region, and the other structured STB segments will be free to persist for many years, with 2 or 3 of them spaced around the S. Temperate domain. Indeed, they may accelerate further to behave like the inter-ovals around 1940. Then after ≤10 years, as in the late 1940s, the spaces between them will develop into anticyclonic circulations that will become the next generation of large ovals.

+++

References

[Papers marked * are available on this BAA web page (http://www.britastro.org/jupiter) under ‘Publications’.]

1. Rogers JH (1995), *The Giant Planet Jupiter*. Cambridge University Press, 1995.

2.* Rogers J, Mettig H-J, Peach D & Foulkes M (2003), JBAA 113 (no.1), 10-31. ‘Jupiter in 1999/2000, Part I: Visible wavelengths.’

3.* Rogers J, Mettig H-J, Peach D, & Foulkes M (2004), JBAA 114 (no.4), 193-214. ‘Jupiter in 2000/2001: Part I: Visible wavelengths: Jupiter during the Cassini encounter.’

4.* Rogers JH, Mettig H-J, Foulkes M, Peach D, & Cidadão A (2008), JBAA 118 (no.2), 75-86 (Part I) and (no.4) pp.203-216. 'Jupiter in 2001/02.'

5. Porco CC et 23 al. Science 299, 1541-1547 (2003). ‘Cassini Imaging of Jupiter's Atmosphere, Satellites, and Rings’

6. Rogers JH (2013) ‘Reference list of Jupiter's Jets’ http://www.britastro.org/jupiter/reference/jup_jets/ref_jets.htm

7.* Rogers JH, Adamoli G & Mettig H-J (2011) JBAA 121 (no.1), 19-29. ‘Jupiter’s high-latitude storms: A Little Red Spot tracked through a jovian year.’

8. Rogers JH, Mettig H-J, Cidadão A, Sherrod PC, and Peach D (2006). Icarus 185, 244-257. ‘Merging circulations on Jupiter: observed differences between cyclonic and anticyclonic mergers.’

9. Sanchez-Lavega A et 12 al.(2001) Icarus 149, 491-495. ‘The merger of two giant anticyclones in the atmosphere of Jupiter.’

10. Rogers J, 2012/13 report no.9: ‘Interim report on Jupiter, 2012 Aug.-Dec.’ http://www.britastro.org/jupiter/2012_13report09.htm

11. Foulkes M & Rogers JH (2000 Oct.) JBAA 110 (no.5), 237-252. ‘Jupiter in 1995.’

12. Garcia-Melendo E, Legarreta J, Sanchez-Lavega A, Hueso R, Perez-Hoyos S, Gonzalez J, Gomez-Forrellad JM, & IOPW team (2009) Icarus 203, 486-498. ‘The jovian anticyclone BA: I. Motions and interaction with the GRS from observations and non-linear simulations.’

13. Rogers J & Herbert D (1991) JBAA 101, 351-360. ‘The three white ovals and adjacent belts in the South Temperate region of Jupiter.’

14. Choi DS, Showman AP & Vasavada AR (2010) Icarus 207, 359-372. ‘The evolving flow of Jupiter’s white ovals and adjacent cyclones.’

15.* Rogers J.H., JBAA 116 (no.5), 226-228 (2006). ‘News note: Jupiter in 2006', & cover: 'A new red spot on Jupiter'.

16. Garcia-Melendo E et 6 al. Icarus 146, 514-524 (2000). 'Long-lived vortices and profile changes in the 23.7ºN high-speed jovian jet.'

17. Adamoli G, Astronomia UAI, no. 5 (2012 Sep.-Oct.), pp. 32-41. 'Giove 2010-2011: rapporto osservativo'.

18. Images from New Horizons from the LORRI instrument: credit NASA, Johns Hopkins University Applied Physics Laboratory, & Southwest Research Institute. A global ZWP was published by: Cheng AF et 14 al. (2008) Astron.J. 135, 2446-2452. 'Changing characteristics of Jupiter's little red spot' (Fig.1d).

19. Hahn G: http://www.grischa-hahn.homepage.t-online.de/index.htm
--For Hahn's ZWPs from New Horizons in 2007, as well as amateur images in 2010, follow:
WinJUPOS / Tutorials / Longitudinal drift determination from image pairs with WinJUPOS

20. Unpublished HST images taken on 2012 Sep.20 by an international team headed by Dr Glenn Schneider (University of Arizona) and Dr Jay Pasachoff (Williams College and Caltech), as part of their project to detect the transit of Venus that was then visible from Jupiter.

21. Vedovato M, 'Jupiter: maps from HST 2012 September 20'.
http://pianeti.uai.it/index.php/Jupiter:_maps_from_HST_2012_September_20

22. Hahn G, in: 2012/13 report no.9: 'Interim report on Jupiter, 2012 Aug.-Dec.'
http://www.britastro.org/jupiter/2012_13report09.htm
--Appendix 5, Fig.14.

23. Hueso R, Legarreta J, Garcia-Melendo E, Sanchez-Lavega A, & Perez-Hoyos S (2009) Icarus 203, 499-515. 'The jovian anticyclone BA: II. Circulation and interaction with the zonal jets.'

24.* Rogers JH & Mettig H-J. (2008), JBAA 118 (no.6), 326-334. 'Influence of Jupiter's South Equatorial Disturbance on jet-stream speed'.

On next page: References to our on-line reports.

S.Temp. domain: the principal reports on our Section web site under ‘Reports’:

2006:
[7] S. Temperate domain: reddened oval BA, and the other circulating complex.
http://www.britastro.org/jupiter/2006report07.htm

[9] Interim reports on STB (Oval BA passing GRS), STropB, GRS...[etc.]
http://www.britastro.org/jupiter/2006report09.htm

[11] Interim reports on the SSTB (cyclonic white ovals break up) and STB (A remnant or a forerunner?)
http://www.britastro.org/jupiter/2006report11.htm

2007:
[20] Jupiter in 2007: Final Numerical Report.
http://www.britastro.org/jupiter/2007report20.htm

2008:
[6] Jupiter in 2008: Full Interim Report.
http://www.britastro.org/jupiter/2008report06.htm

2009:
[6] Jupiter in 2009: An interim report.
http://www.britastro.org/jupiter/2009report06.htm

[7] Jupiter in 2009: Interim Report, with new insights into the NTZ disturbance, NEB expansion, and SEB fading.
http://www.britastro.org/jupiter/2009report07.htm

2010/11:
[4] A triple collision of long lived circulations in the S. Temperate domain.
http://www.britastro.org/jupiter/2010report04.htm [Important long report]

[8] Jupiter in 2010: Interim report: Southern hemisphere.
http://www.britastro.org/jupiter/2010report08.htm

[also see reports nos.6 & 12 for STBn jetstream spots interacting with GRS]

Text from some of these reports is reproduced in Appendix 4.

Table 1.

Average latitudes and speeds of jets from published spacecraft data.

This is an excerpt from a table that we have posted [ref.6], q.v. for references.

	From Voyager, 1979			From Hubble (1995-1998)			From Cassini, 2000			From New Horizons, 2007		
	(Limaye, 1986)			(G-M & S-L, 2001)			(Porco et al., 2003)			[Cheng et al., 2008]		
	[as in Rogers, 1995]						[Data from A. Vasavada]			[data from A.Cheng & A.Simon]		
Jet/belt	Lat.B"	u3	DL2	Lat.B"	u3	DL2	Lat.B"	u3	DL2	Lat.B"	u3	DL2
SSTBn	-36,5	31,6	-88	-36,3	40,2	-109,4	-35,8	34,2	-94,0	-36,5	46,8	-126,2
STBs	-32,6	-20,8	42	-32,3	-11,6	20,0	-32,0	-16,1	30,7	-32,2	-17,0	33,0
STBn	-27 to -29	44,3	-110	-26,4	56,8	-138,2	-26,7	48,1	-118,6	-26 to -29	46,7	-115,7
							& -29,2	24,5	-65,5			

	AVERAGE VALUES		
Jet/belt	Lat.B"	u3	DL2
SSTBn	-36,3	38,2	-104,4
STBs	-32,3	-16,4	31,4
STBn	-26,5	49,0	-120,6
	& 29	(var)	

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

Table 2:

2001-2012 dark spots Sf. STB segments :

Mean speeds of spots at lats. 31.5 to 32.8 (STBs jet)

Apparition	*DL2(°/30d)*	*+/-SD*	*U3 (m/s)*	*Lat.*	*+/-SD*	*n*
Spots f. segment A						
2001-02	**-0,3**	1,5	-3,2	**-32,5**	0,3	3
2003-04	**12,7**	1,5	-8,5	**-32,6**	0,1	3
2005	**27,6**	2,3	-14,7	**-32,3**	0,2	3
2006	**5,9**	0,1	-5,7	**-32,7**	0,1	3
	33,4	2,2	-17,1	**-32,2**	0,3	5
J6	43,2		-21,3	-31,9		1
2007	**14,5**	3,2	-9,3	**-32,4**	0,6	4
	26,9	1,2	-14,6	**-31,5**	0,2	4
J5	44,1		-21,7	-31,7		1
2008	**18,1**	2,7	-10,9	**-31,8**	0,3	8
2010 & 2011	**6,7**	1,9	-6,1	**-32,2**	0,2	5
Spots f. segment D						
2010 & 2011	**15,2**	8,5	-9,6	**-32,5**	0,1	4

(Single outlying values are omitted, except single spots labelled J6 and J5.)

Table 3.
Oval BA: Speed, latitude, length, and colour

Tme interval	ΔL2(°/30d)	Lat.		Length			Redness
			SD		SD	N	
2000 Jul 11 - 2001 Feb 10	-12,3	-32,2	0,58	9,9	0,7	32	O
2001 Sep 17 - 2001 Dec 21	-13,1	-32,6	0,47	9,8	0,9	4	O
2001 Dec 25 - 2002 Feb 13	-10,9	-32,4	0,53	10,7	0,6	23	O
2002 Feb 14 - 2002 Apr 21	-13,4	-32,6	0,68	11,7	0,9	26	O
2002 Nov 7 - 2003 May 8	-10,4	-32,2	0,49	9,1	0,7	18	O
2003 Dec 16 - 2004 May 20	-12,6	-33,0	0,40	9,0	0,9	35	O
2004 Oct 20 - 2005 Mar 7	-12,7	-32,7	0,44	10,8	1,0	16	O
2005 Mar 10 - 2005 May 23	-14,4	-32,9	0,42	11,4	0,8	26	O
2005 May 25 - 2005 Sep 8	-14,3	-32,7	0,40	11,3	0,3	10	O
2006 Mar 18 - 2006 Jun 28	-13,3	-32,8	0,34	11,7	0,8	34	++
2006 Jul 1 - 2006 Sep 18	-15,7	-32,8	0,35	12,3	1,5	24	++
2007 Jan 21 - 2007 Apr 24	-15,3	-32,7	0,21	11,8	0,7	9	++
2008 Feb 21 - 2008 Jun 10	-14,2	-33,1	0,33	9,8	0,9	32	+
2008 Jun 12 - 2008 Aug 8	-15,5	-33,1	0,40	10,0	0,7	13	+
2009 Mar 11 - 2010 Jan 15	-11,9	-32,7	0,28	11,0	0,8	57	(+)
2010 Apr 8 - 2010 Jul 28	-11,6	-32,9	0,32	8,7	0,8	6	++
2010 Sep 16 - 2011 Jan 8	-16,5	-33,3	0,23	7,9	0,5	17	++
2011 Jul 24 - 2011 Aug 25	-18,9	-33,2	0,20	8,6	0,3	12	(+)
2011 Sep 5 - 2011 Dec 3	-11,1	-32,9	0,24	8,8	0,8	29	(+)
2012 Jul 22 - 2012 Sep 22	-11,7	-33,2	0,18	6,5	0,2	13	++
2012 Sep 29 - 2013 Jan 13	-10,4	-33,1	0,22	7,2	0,7	20	++

These data are for track segments with fairly steady drift for at least two months, except 2011 Jul-Aug., which was not plotted on Fig.11.
Length is derived mainly from colour images, as well as white-, red-, or green-light images in the early years.
Lengths were also derived from red or infrared images only, to check whether there was confusion with the orange annulus, but these showed no significant difference from the full-spectrum measurements, except in 2006-2007 when the latter tended to be larger and highly scattered, for unknown reason. (The value for 2006 July-Sep. is not plotted in Fig.13 for this reason.) N is for length only; N for drift and latitude was much larger.
Standard error of latitude is <0.1º because tens of points were averaged for each spot. Uncertainty in drift rate is conservatively estimated as 2 x 0.4º divided by track duration in months; typical uncertainty for a 2-month track is thus 0.4º/month, but in practice the precision is usually limited by real fluctuations in drift rate.

Table 4.
Oval BA: colour

Time interval	*Redness*
up to 2005 Apr	O
2005 Dec - 2006 Mar	+ --> ++
2006 Apr - Sep	++
2007 Jan - Oct	++ -> +
2008 Feb - Oct	+
2009 Mar - Nov	(+)
2009 Dec - 2010 Jan	(+) --> +
2010 Apr - 2011 Feb	++
2011 Jun - 2012 Feb	(+)
2012 Jun - 2013 Mar	++

Colour was assessed visually from images.
This table covers the whole of each apparition.

Table 5:

Table 5.	**Speeds of STBn jetstream spots**							
Appar'n	*DL2 (deg/month):*			*Lat*	*N*	*Source*	*Overview*	
	Min	*Mean*	*Max*	*(S)*				
1999/00	-60	-77	-113	27	many	*BAA report*	First outbreak since 1994, arising near DS1/DS2, from 199 Aug. onwards.	
2000/01						*BAA report*	No visible activity. (Cassini tracked v.small spots.)	
2001/02	-85	-99	-110	26,8	3	*BAA report*		
2002/03						*JUPOS (HJM)*	No visible activity.	
2003/04		-75			4	*JUPOS (HJM)*	F. GRS	Major outbreak p. BA (after STB segments collided)
	-80	-87	-94		11		P. GRS.	
2005	-84	-90	-95		13	*JUPOS (prelim)*	Arising just p. BA.	
2006	-79	-89	-103	28,5	7	*JUPOS (GA)*	Still many spots.	
	-75			27,5	1			
2007	-96	-96	-98	28,2	9	*BAA/JUPOS*	A few small spots intrinsic to STBn jet.	
	-61	-76,5	-94	26,4	9	*report (online)*	Many spots recirc. at STropD from SEB Revival; only single ones listed here.	
2008		-99			many	*JUPOS (prelim)*	V.small spots arising p.GRS.	
2009		-82			many	*Interim (online)*	Many spots arising at p. edge of segment D.	
2010	-64	-76	-91	28,0	many	*UAI(GA) &*	Major outbreak p.BA (as STB segments collided) and	
						this report	p. segment D, during SEB Fade.	
			-110		2	*Interim (online)*	Within STB Rem.colliding with BA.	
2011/12	-85	-93	-103	27,5	many	*UAI(GA) &*	Many spots but much smaller than in 2010.	
						this report		

Table 6:

Latitudes and speeds of jets from sectoral zonal wind profiles

Jet peaks from ZWPs: Structured sectors

	From NH (2007 Jan.)			From HST (2012 Sep.)			Amateur (2012 Nov.)			AVERAGES					
	B"	u3	DL2	B"	u3	DL2	B"	u3	DL2	B"	(+/-SD)	u3	(+/-SD)	DL2	(+/-SD)
										(Lat.)		(m/s)		(deg/mth)	
SSTBn	35,7	41,4	-111,6	35,4	50,4	-133,7	36,1	44	-119	35,7	0,35	45,3	4,6	-121,4	11,2
STBs	32,0	-23,0	47,4	31,8	-38,1	83,5	32,2	-10	16	32,0	0,20	-23,7	14,1	49,0	33,8
STBn(S)	28,7	44,0	-110,7	28,8	45,4	-114,0	28,7	43	-108	28,7	0,06	44,1	1,2	-110,9	3,0
STBn(N)	24,9	24,0	-62,3	26,0	47,7	-117,0	26,3	45	-111	25,7	0,74	38,9	13,0	-96,8	30,0

Jet peaks from ZWPs: Undisturbed sectors

(means of 2 sectors each)	From NH (2007 Jan.)			From HST (2012 Sep.)			Amateur (2012 Sep,Dec.)			AVERAGES					
	B"	u3	DL2	B"	u3	DL2	B"	u3	DL2	B"	(+/-SD)	u3	(+/-SD)	DL2	(+/-SD)
										(Lat.)		(m/s)		(deg/mth)	
SSTBn	35,6	35,5	-96,9	35,4	44,6	-119,1	35,8	42	-113	35,6	0,20	40,7	4,7	-109,7	11,5
STBs	32,0	-15,1	28,4	31,8	-16,6	32,1	31,9	-15	28	31,9	0,10	-15,6	0,9	29,5	2,3
STBn(S)	29,0	38,8	-98,9	[29,0]*	[23,1]	[-61,9]	--	--	--	29,0	--	31,0	11,1	-80,4	26,2
STBn(N)	26,2	31,0	-78,8	26,8	41,1	-102,5	27,0	40	-100	26,7	0,42	37,4	5,5	-93,8	13,0

Jet peaks from spot tracking (JUPOS data)

	(1999-2002)			(2005-2007)			(2011/12)			AVERAGES					
	B"	u3	DL2	B"	u3	DL2	B"	u3	DL2	B"		u3		DL2	
										(Lat.)		(m/s)		(deg/mth)	
SSTBn (fastest spot)	(35)	28,0	-77,5	36,5	39,1	-107	36,0	42,2	-114	36,3		40,7		-111	
SSTBn (peak group)				**35,5**	**34,7**	**-94,8**	**36,0**	**40,8**	**-110,5**	**35,8**		**37,8**		**-102,7**	
(+/-SD)				(n=4)		4,9	(n=4)		4,0						
STBs (fastest spot)				31,7	-21,7	44,1				31,7		-21,7		44,1	
STBs (peak group)				**31,9**	**-16,5**	**31,8**				**31,9**		**-16,5**		**31,8**	
(+/-SD)				(n=13)		6,1									
STBn (fastest spot)	(27)	45,6	-113	28,7	40,7	-103	27,7	41,0	-103	27,8		42,4		-106	
STBn (peak group)				28,3	35,6	-91	**27,5**	**39,2**	**-98,6**	**27,5**		**39,2**		**-98,6**	
(+/-SD)				(n=29)			(n=9)		2,8	(broad peak from 26,8 to 28,5 S)					

*This entry is for a shoulder on the ZWP, as there was no peak.

For the SSTBn jet, we give values from 2000/01 , 2005, and 2011/12, years in which there were substantial outbreaks of fast-moving dark spots.

(2000/01: published BAA report; 2005 and 2011/12, unpublished JUPOS analysis by G. Adamoli)

In each case there was a wide range of speeds, north of the jet peak, which were shown to fit well on an anticyclonic gradient in 2005 and 2011/12.

FIGURE LEGENDS

South is up in all figures.

Figure 1. The S. Temperate domain, 1994-2000.
(A) Maps in each apparition, 1994-2000. All are cylindrical projection maps, published in our reports in the *Journal of the BAA*, except the HST map in 1994 (see credits on figure). South is up. Maps are aligned on oval BC/BE/BA. CD and YF were cyclonic ovals: YF was designated the 'Morphing Spot' because of extraordinary changes in its colour and appearance (Appendix 1).
(B) Spacecraft images of the new structured STB sector, in 1999 June & Oct. (from Hubble Space Telescope) and 2000 Dec. (from Cassini). The main features are the new dark STB segment (DS2) and the small, very dark anticyclonic oval Sf. it (DS3). Shorter arrows indicate two small cyclonic spots (probably DS1 and DS1b). Credits on figure. (More spacecraft close-ups of these spots are shown in our reports [refs.2 & 3] and in **Fig.2.)**

Figure 2. Part of the Cassini map on 2000 Dec.11-12, showing details of a typical STB structured sector (right half), compared with an undisturbed sector (left half), on which the approximate jet latitudes are marked. (Credit NASA/JPL/University of Arizona). This map is used as it has an equirectangular projection which does not distort high-latitude features excessively.

Figure 3. Maps in each apparition, 2000-2011. One of the best available maps for each apparition is shown, covering latitudes from the south pole down to mid-SEB, with the S. Temperate features labelled. Black bars above mark the extent of STB structured sectors, including STB dark segments A and B as labelled in the early maps. On some maps the S.S.Temperate AWOs are also indicated (labels in blue). All maps use cylindrical projection and System II longitude (L2), and were made using WinJUPOS, except the Cassini map which uses equirectangular projection.

Figure 4. JUPOS charts for the S. Temperate domain.
(A,B) Charts of longitude vs. time, for 29-34ºS. Longitude is plotted in System III (L3 = L2 – 8.0 deg/mth); oblique pale blue line marks L2 = 0. Black points, dark features (31-34ºS); green points, oval BA (31-34ºS); red points, bright features (31-34ºS, mostly small AWOs); grey points, dark features (29-31ºS, i.e. belonging to cyclonic STB or to the edge of the STBn jetstream). Oblique pink line is the track of the GRS. < > indicate p. and f. ends of dark sectors; some dark STB segments are highlighted by grey shading. The track of the STB Remnant was not always clear from the JUPOS chart, because of its irregular extended nature, but has been plotted from inspection of images.
(C) Summary chart. Longitude = L2 – 13.0 deg/mth. Grey shadings indicate dark STB segments. Green, oval BA; blue, p. end of structured sector; purple, f. end; B', small feature (DS1b) p. main part of sector B.

Figure 5. Growth of the three new STB structured sectors, shown in charts of length (in degrees longitude) vs time. The two dark segments steadily increased in length: segment B at a rate of 0.6 deg/mth increasing to 1.0 deg/mth; segment D at a rate of 1.1 deg/mth increasing to 1.6 deg/mth. In contrast, segment C (the STB Remnant) only showed modest and inconsistent growth.

Figure 6. Images showing oval BA and the STB f. it in 2003/04, when rapid changes took place due to the impact of small cyclonic region DS1b followed by the large dark STB segment B. See text for details. 'FFR', folded filamentary region (turbulent sector of STB).

Figure 7. Image sets showing early stages of the STB Remnant and a similar feature.
(A) Origin of the STB Remnant from a v.d.s. (dsA) in spring, 2004.
(B) The STB Remnant in 2005.
(C) A cyclonic very dark spot (DS4) fading in 2012 autumn, within a blue-grey streak, which could be the origin of a new structured sector similar to the former STB Remnant. The spot becomes reddish as it fades to pink. By 2013 Jan. it was a small white oval within the faint blue-grey streak.

Figure 8. Charts of speed vs latitude for dark spots in the Sf. extensions of STB segments, from JUPOS data, with the Cassini ZWP for comparison, covering the STZ and the retrograding STBs jet at 32ºS. (A) All spots, 2000-2012. The large scatter is resolved into multiple ZDPs in the following panels. (B) All spots in 3 time intervals. Spots mostly lie close to the Cassini ZWP, except for two groups: (i) Spots at 32ºS reached the full retrograding jet speed only in 2004-2007, but not in other years. (ii) Spots f. the STB Remnant (segment C) in 2005-2007 lay south of the Cassini ZWP. They are marked +; coloured lines indicate changing speed/latitude for individual spots. Most of the spots in group (ii) had been recirculated from the SSTBn prograde jet at the f. edge of the STB Remnant, and all such spots are shown in (C), including a few very small spots not included in the previous charts. (Analysis by G. Adamoli)

Figure 9. Views of oval BA from 2006 to 2012, in cylindrical projection maps from Fig.3.

Figure 10. JUPOS charts for oval BA, 2001-2012. Longitude = L2—0.45 deg/day. Pink line is track of GRS.

Figure 11. Zonal drift profiles for oval BA and its predecessors.
(A) Speed versus latitude for oval BA, year by year, 2000-2012.
(B) Speed versus latitude for the previous 3 long-lived ovals. Data for 1940-45 and 1950-78 were published in [ref.13, & ref.1 p.227]. For subsequent years, the data have been re-examined and sorted by the lengths of the individual ovals.
(C) Trend lines from (B) overlaid on (A), showing that the ZDPs are identical when the ovals have similar sizes. The shaded area marks the locus of most points for 1984-96 when the ovals were 7-8º long; there was too little variation to establish a gradient. (The few points for lengths <7º were scattered and are not shown.)

Figure 12. Passage of oval BA past the GRS in 2010. The position of BA is plotted to scale in latitude, relative to the GRS, showing how it suddenly shifted in latitude from 32.9 to 33.3ºS, when it also accelerated, exactly at conjunction. (Oval outlines are shown diagrammatically; note that longitude scale is compressed.)

Figure 13. Length of oval BA.
(A) Length of oval BA throughout its lifetime, from the data in Table 3 (white-light images). There was little change from 2000-2007, but significant shrinkage since 2007.
(B) Chart of length vs latitude. Since 2007 there has been a significant correlation, consistent with the hypothesis that the southward shift of BA's ZDP is due to its shrinkage. Latitudes before 2004 were anomalously low, probably because of the asymmetric shape of the 'oval'.

Figure 14. JUPOS chart for the STBn jetstream, 2001-2012 (dark spots only, latitudes 26-29ºS; longitude = L2 – 2.00 deg/day). Oblique green line marks the track of oval BA. The density of points has increased over the years due to better imaging, but there were also real increases, most notably in 2003/04 and 2010.

Figure 15. Measurements of the STB latitudes in 2006 and 2010, from images by Italian observers (UAI, by G. Adamoli). Grey bands highlight the STB sectors. Note that the STB(N) trends north for ~80-180º p. oval BA.

Figure 16. Drifts of STBn jetstream spots in 2010.
(A) Tracks of individual STBn jetstream spots in 2010 which moved north during their lives. Each colour/symbol denotes one spot.
(B) Chart of speed vs mean latitude for all STBn jetstream spots measured in 2010, compared with the ZWP from Cassini.
Data in these charts were from Italian observers, and the results were published in [ref.17], which stated:

> 'The numerous spots of the STBn (...) jetstream lay in agreement with the local wind profile as measured by spacecraft. Some spots of the STBn jetstream, born near the p. edge of one of the dark sectors of the STB, had their latitude progressively diminishing during their eastward motion. That may be linked to the latitude variation of the belt, which the spots adhered to.'

Figure 17. Drifts of STBn jetstream spots in 2011.
(A) Tracks of individual STBn jetstream spots in 2011 which moved north during their lives.
(B) Chart of speed vs mean latitude for all STBn jetstream spots measured in 2011, compared with the ZWP from Cassini. Five spots moved north during their lives through a latitude range indicated by vertical lines. (JUPOS data.)

Figure 18. Zonal wind profiles and map from New Horizons images in 2007 Jan. (analysis by Grischa Hahn). [See refs.18 & 19.] The ZWPs were obtained by correlation between maps made from sets of images two rotations apart, taken on 2007 Jan.8-10, 14-15, and 20-22, in white light. (A) ZWPs in 4 sectors (defined as in the map below): averages for all dates. Asterisk marks the STBn jet sub-peak at 29ºS, strongest in the structured sector. (B) The same with data from individual dates plotted. (C) A representative map, defining the 4 sectors. Also note the presence of two South Tropical Disturbances, although these do not appear to have perturbed the intrinsic flow of the STBn jet south of 26ºS.

Figure 19. Zonal wind profile and map from Hubble Space Telescope images on 2012 Sep.20 (analysis by Marco Vedovato). [See refs.20 & 21.] The ZWPs were obtained by correlation between maps made from sets of images one rotation apart, in near-infrared light. Asterisk marks the STBn jet sub-peak at 29ºS, strongest in the structured sector. ZWPs are shown in 4 sectors, defined as in the map below.

Figure 20. Zonal wind profiles from amateur images in 2012 Sep-Dec.; at bottom is one map from each pair. (Analysis by Grischa Hahn; image dates and observers as listed on the figure). It is more difficult to extract an absolute ZWP from ground-based images than from spacecraft images, because of possible errors in timing and limb-fitting, so empirical global offset has been applied to some profiles to optimise the fit. Nevertheless, the profiles agree well with each other and with spacecraft ZWPs, and the STBn jet sub-peak at 29ºS (asterisk) is a notable difference between the structured and undisturbed sectors.

Figure 21. Summary of the mean parameters of the jets in the structured and undisturbed sectors. This is an updated version of **Fig. 2**, showing the true relative speeds of the jets in different sectors, with data derived from **Figs.18-20 (Table 6)**. The base map is from 2011 Sep.24-30 by Damian Peach.

Appendix 1

The 'Morphing Spot, 1994-1998.

[see BAA reports inc. 1995 (ref.11) & 2001/02 (ref.4); the report for 1994, by Mike Foulkes and J.R., is still unpublished]

This was a cyclonic oval within the STB between a small AWO (labelled XY in **Fig.1A**) and oval FA. It is labelled YF in **Fig.1A**. It was tracked in amateur images during 1994, within a distinct dark segment of STB. In 1994 Feb-March it was a very dark reddish-brown barge. In April it was a bright yellowish streak, which then turned dark again and merged into the STB, while a lighter cyclonic area formed f. it (persisting through July). From May to July there were only small-scale changes, and in July-August, a darker reddish segment in the northern STB. The HST map in 1994 July showed the STB segment as dark grey with the morphing spot as a small red-brown oval within it. Another HST map in 1995 Feb. showed it as a very small, very dark brown oval. Amateur images showed it as a tiny red spot in 1995 April-May, which disappeared into a white strip in June, being replaced by a distinct white oval in July-August.. In 1996 (April-Oct.) it was still a white oval, swinging to and fro between AWOs XY and FA. In 1997 (May-Oct.), oval XY had disappeared, but a cyclonic oval which may well have been the morphing spot still existed as a vivid red spot, within dark STB, wandering to and fro between AWOs DE and FA. After ovals BC and DE merged in early 1998, the STB between the new AWO and oval FA contained bright or reddish patches for several months, with a distinct cyclonic white oval from July to Nov., so this may have been the final form of the morphing spot.

Appendix 2

Typical profiles of jovian jets

[see ZWPs from spacecraft referenced in ref.6]

Prograde jets are notably sharp and rapid, and largely invariant. Small dark spots sometimes observed on them are typically anticyclonic vortices, running along the anticyclonic (low-latitude) side of the jet peak, slightly slower than the peak wind speed. This has been documented for the following jets:

NTBs [ref.16].

NNTBs [Voyager images, & our unpublished data].

STBn -- the recirculated spots in 2007, which showed a clear anticyclonic gradient below 27ºS. [ref. 'Reports', 2007 no.20, Part 3, esp. Box and Figs.13&14 therein].

SSTBn [new JUPOS data: Section 7.3 & Table 6]: The SSTBn is a typical prograding jet, with little variation in speed or latitude in spacecraft data. In our JUPOS tracking data, most of the spots are actually slightly north of the jet peak, drifting more slowly, and follow the anti-cyclonic gradient of the STZ. This suggests that these may be anticyclonic vortices as on other prograde jets. The very fastest spots, singly or in groups (**Table 6**), have mean DL2 ~ -106 deg/mth (u ~ 39 m/s), at 36.0ºS, which is still marginally slower than the mean wind peak: -116 deg/mth (u ~ 43 m/s) at 35.6ºS, although the difference in speed and latitude is not statistically significant.

The only retrograde jet which is as fast and sharp as the prograde jets is the SEBs jet. Likewise, it carries spots which are anticyclonic vortices, running along the anticyclonic side of the jet peak, as shown in Voyager and Cassini images, and during the 2007 SEB Revival [ref. 'Reports', 2007 no.20, Part 3, esp. Box and Figs.13&14 therein].

Other retrograde jets: ZWPs from spacecraft indicate that most retrograding jets are not as fast nor sharp as the prograde jets; those at latitudes >40º are particularly weak and broad. They do not carry well-defined spots and their peak speeds are only rarely detectable in ground-based images.
The STBs jet is as sharp and constant as many prograde jets (Table 1). Nevertheless, we confirm that it is not a well-defined dynamical boundary: the dark spots which approach it are able to wander in latitude (some move southwards across it), and most of them appear to be amorphous patches, with no evidence of vorticity.

Appendix 3

Studies of oval BA from spacecraft

Professional references on Oval BA since it turned red
(studying its colour and its circulation, and testing computational models of it):

Simon-Miller AA et al.(2006) Icarus 185, 558-562.
Cheng AF et al.(2009) Astron.J. 135, 2446-2452.
Asay-Davis XS et al.(2009) Icarus 203, 164-188.
Garcia-Melendo E et al.(2009) Icarus 203, 486-498.
Hueso R et al.(2009) Icarus 203, 499-515.
Perez-Hoyos S et al.(2009) Icarus 203, 516-530.
Choi DS, Showman AP & Vasavada AR (2010) Icarus 207, 359-372.
Shetty S & Marcus PS (2010) Icarus 210, 182-201.
Sussman MG et al.(2010) Icarus 210, 202-210.
de Pater I et al.(2010) Icarus 210, 742-762.
Wong MH et al.(2011) Icarus 215, 211-225.

The data were largely summarised by Hueso et al.(2009) and Choi et al.(2010).

Wind speed and dimensions of oval BA

The main question was whether the wind speed increased when the red colour appeared in 2005/06. This has been debated at length, but all comparative studies show a modest, possibly significant increase in mean wind speed, if not in the fastest single vectors. The average of values published for the mean peak wind along the S edge is 111 m/s (+/-7 m/s; n=4) from the Cassini data and 120 m/s (+/-17 m/s; n=3) from the New Horizons data.

These reports are more consistent in regard to the size and shape of oval BA, as defined by the contour of maximum wind speed. All agree that in 2000/01, BA was a ‘triangular oval’ not only in its visible outline but in its flow pattern, which had a northern extension across the STB to 29.8 (+/-0.2) °S. (Hueso et al., 2009, showed that this asymmetry was due to the interaction of oval BA with the surrounding ZWP, especially the jets.) By 2006 and 2007, the triangular form was less marked and the northern edge of the maximum-wind contour was at 30.6 (+/-0.4) °S. In contrast the dynamical centre and south edge had shifted south by just 0.4° – attributable to the faster drift rate in 2006-07 – so the oval had narrowed from 5.4° to 5.0° in width.

Dimensions and wind speeds of oval BA from spacecraft

		Cassini 2000 Dec	(+/-)	N	HST 2006 April	(+/-)	N	NH 2007 Feb.	(+/-)	N
S edge	Speed	**110,8**	7,1	4	**125,5**	0,7	2	**119,7**	17,5	3
S edge	Lat	**35,2**	0,3	3	**35,1**	0,3	2	**35,6**	0,6	3
Centre	Lat	**32,6**	0,1	2	**32,3**		1	**33,0**	0,4	3
N edge	Lat	**29,8**	0,2	3	**30,8**	0,1	2	**30,6**	0,4	3
N edge	Speed	**68,3**	3,5	4	**87,5**	3,5	2	**86,8**	7,6	3

Data from Cheng et al.(2008), Asay-Davis et al.(2009), Hueso et al.(2009), Sussman et al.(2010), Choi et al.(2010).
Latitudes are zenographic. The latitude of the dynamical centre is given.
Quoted uncertainties are the standard deviation of the published means, thus effectively the standard error of the mean. Speeds are in m/s.