

# Jupiter's North Equatorial Belt & Jet

## I. Cyclic expansions & planetary waves

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*A report of the Jupiter Section, using data from the JUPOS team*

This article presents a synopsis of the activity in Jupiter's North Equatorial Belt (NEB) from 1986–2010, and of the speeds of dark formations on its south edge and bright streaks ('rifts') in its interior. In particular I discuss NEB expansion events (NEEs), which took place every 3–5 years during this time, and how the various features of the NEB are involved in them.

I present evidence that the NEE affects not just the northern edge, but the whole width of the belt. It begins with an outbreak of a bright rift that is more northerly and slower-moving than usual; this is often involved with the first ejection of dark material northwards into the N. Tropical Zone, but typically the rift also expands southwards across the width of the NEB. NEBs dark formations are usually affected, as they are during individual interactions with rifts at other times; they may be disrupted, or intensified, and they usually undergo deceleration. The expansion of the dark NEB to the north occurs concurrently, and is followed by the appearance of new dark 'barges' and white ovals flanking the NEBn jet.

The speed of the NEBs dark formations varies with their mean spacing, consistent with the prevailing hypothesis that they are planetary Rossby waves. In most apparitions since 2000 we have also detected smaller, faster features (~120 m/s). I propose that these represent waves of the same type, but with higher frequency, and that their speed is slightly less than the true wind speed at cloud-top level under normal conditions.

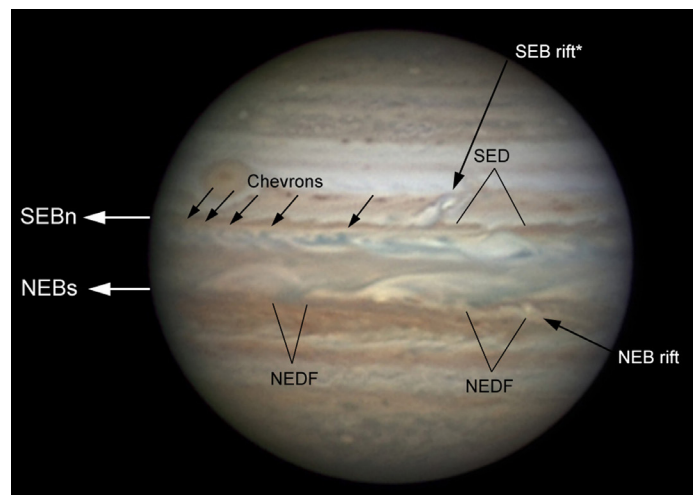
## I. Introduction

### The North Equatorial Belt (NEB)

Jupiter's North Equatorial Belt (NEB) is one of the broadest and darkest belts on the planet. It is almost always a scene of notable weather formations and activity (Figures 1 & 2).<sup>1,2,3</sup> Nominally bounded by the retrograde jet at 17°N on its northern edge (NEBn), and the very fast prograde jet at 7°N on its southern edge (NEBs), the visibly dark belt does not always respect these limits (note that Planetographic Latitudes are used throughout). There is a continuous gradient of wind speed across the NEB – as shown by zonal wind profiles (ZWP) from spacecraft – from the NEBs jet on the south edge (close to System I), to the North Tropical Current which governs the barges and AWOs on the north edge (close to System II). This gradient is demonstrated in Figure 3.

The northern edge usually shows irregularities, which often include prominent oval circulations: dark brown cyclonic ovals ('barges') at 15–16°N, anticyclonic white ovals (AWOs) at 18–20°N; and sometimes anticyclonic dark spots (ADSs) at ~19°N which may be grey, brown or reddish. The latitudes of barges and AWOs vary slightly according to their drift rate, but do not depend on whether they are surrounded by dark 'belt' or bright 'zone' material.

Within the belt there are usually white 'rifts', *i.e.*, oblique, turbulent streaks which are cyclonic convective regions. They are often initiated or renewed by the appearance of brilliant white spots, which are thought to be convective plumes arising by moist convection from the deep water-cloud layer. These are almost certainly thunderstorms, as observed in the NEB rifted region by *Voyager* and *Galileo*.<sup>4,5</sup> The latter spacecraft also observed them in the SEB,<sup>5,6</sup> and they were detected in similar cyclonic turbulent regions elsewhere in the planet by *Voyager* and *Cassini*.<sup>7</sup> The bright spots spread out obliquely as they are sheared by the wind gradient. They often expand into – or form within – more extensive rifted regions, which can last for months or even years.

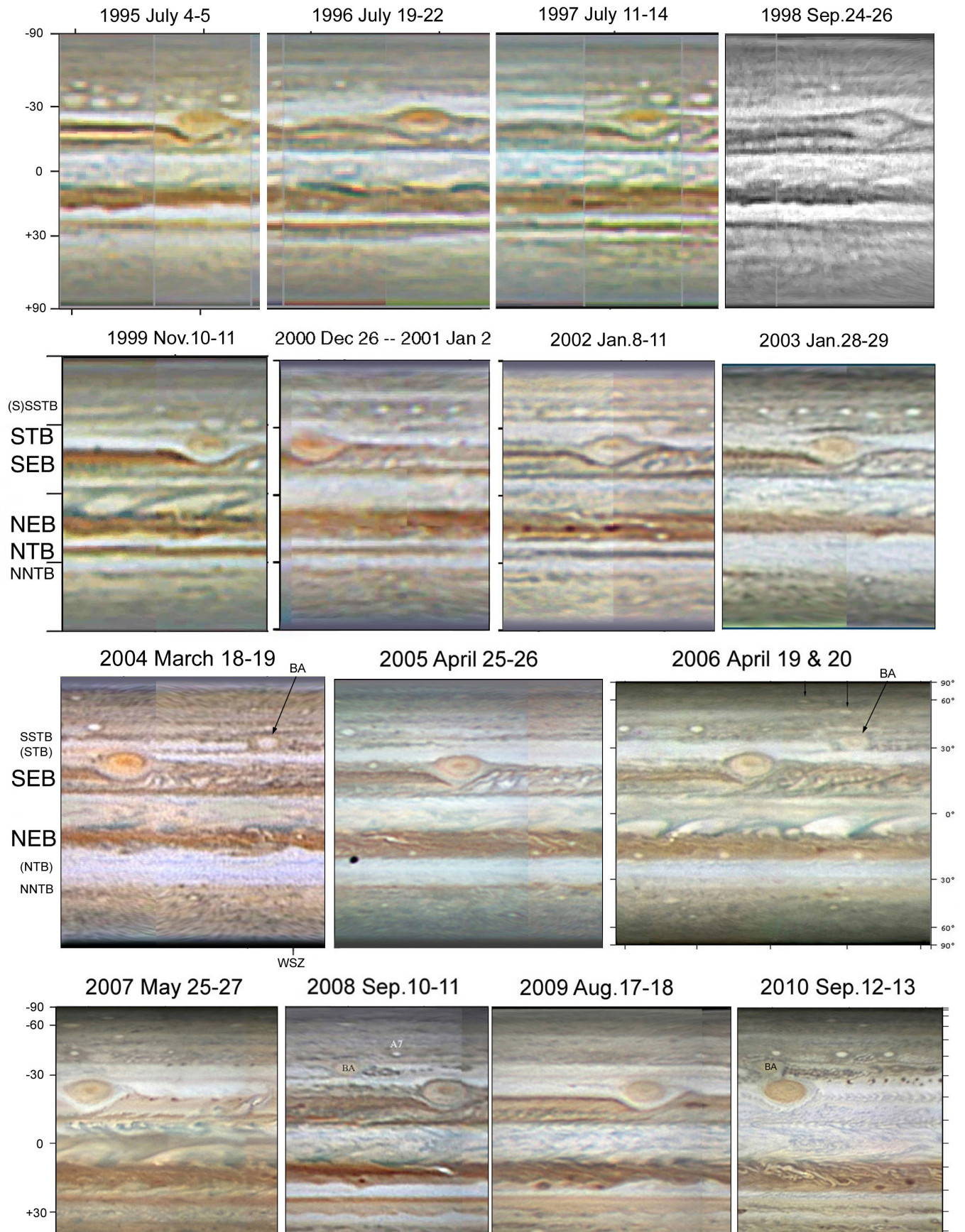


**Figure 1.** Hi-res image of the planet showing typical NEDFs, and a comparable large-scale wave structure in the southern Equatorial Zone called the South Equatorial Disturbance (SED), as well as small super-fast spots on the SEBn jet called chevrons, and rifts in both NEB and SEB. South is up in all figures. Image taken on 2007 May 25 by D. Peach.

On the NEB southern edge, there are large dark formations which are among the most conspicuous features on the planet, as described below. They are often associated with bright white features which are called 'plumes', since their appearance is suggestive of cloud streaming vertically and/or horizontally.

### NEBs dark formations (NEDFs)

From their visual appearance, the NEBs dark formations are usually called 'projections' (extending from the dark NEB into the bright Equatorial Zone (EZ)). Those that are longer but less 'projecting' are called 'plateaux'; and long, grey streaks curving from them into the EZ are called 'festoons'. The dark formations are



**Figure 2.** Alignments of map sectors from 1995–2010, showing NEEs. These all include the GRS, and some include oval BA (labelled). A similar set showing White Spot Z is in our long-term report on it.<sup>28</sup> Scale marks at bottom of some panels are at intervals of 30° longitude. Sources are as follows: for 1995–1999, images by *I. Miyazaki*, maps by *H.-J. Mettig* (mostly published in our reports in the Journal). Intensities and colours have been arbitrarily adjusted so should not be used for comparisons. South is up in all figures. For 2000–’02, images by *A. Cidadao* and *T. Akutsu*, maps by *H.-J. Mettig*. For 2004, images by *D.C. Parker*, map by *D. Peach*. For 2003, 2005, 2006, 2007 & 2010, images and map by *D. Peach*. For 2008, images by *A. Wesley* & *M. Salway*, map by *M. Vedovato*. For 2009, images by *T. Barry*, *C. Go* & *T. Akutsu*, map by *M. Vedovato*. Intensities and colours have been arbitrarily adjusted so should not be used for comparisons. South is up in all figures.



**Figure 3(a).** Chart of speed vs. latitude across NEB in 2003/04 [Interim reports on Jupiter in 2003/04, no.5].<sup>30</sup> Latitudes of white spots (w.s.) and dark spots (d.s.) were assigned to the nearest half-degree by comparison of the visibility of tracks on JUPOS charts at 1° latitude increments, prepared by H.-J. Mettig. Most drift rates are accurate to  $\pm 4^\circ/\text{mth}$ , but open squares indicates less precise drift rates (due to spots with shorter lifetimes or more variable drifts), accurate to perhaps  $\pm 10^\circ/\text{mth}$ . In the range 17–19°N, these open squares are sequential values for Little Brown Spots which were oscillating with periods of  $\sim 20$  days. Symbols are circled for large spots which would have been tracked visually: white spot Z on NEBn, and averages for two groups of dark projections on NEBs. The larger scatter of drift rates at low latitudes may be because some spots are associated with the NEDFs, while others have faster speeds following the overall gradient.

**(b).** Chart of speed vs. latitude across NEB in 2007, produced as in (a); enlargement of data in our 2007 report.<sup>20</sup>

very bright (warm) at thermal infrared wavelengths near  $5\mu\text{m}$  (microns), and are therefore also called ‘hot spots’. ‘Projections’ is not an ideal term, as they can adopt a variety of shapes and are actually distinct weather systems, quite separate to the adjacent belt. Their dark grey or blue-grey colour is different to the brown of the NEB, and they are uniquely conspicuous in the thermal infrared. Here we refer to them as NEBs dark formations (NEDFs).

The NEDFs comprise clearings in all the major cloud layers.<sup>8,9</sup> There are typically  $\sim 10$ – $12$  NEDFs, spaced fairly evenly around the circumference (Rogers, 1995, pp.132–145).<sup>1</sup> Their lifetimes range from months to years. They have drift rates close to System I (equivalent to wind speed  $u = 105.5\text{m/s}$  in System III), commonly in the range from  $\sim 100$ – $110\text{m/s}$ . The average from 1891–1991 was  $107 (\pm 2)\text{m/s}$ .<sup>1</sup>

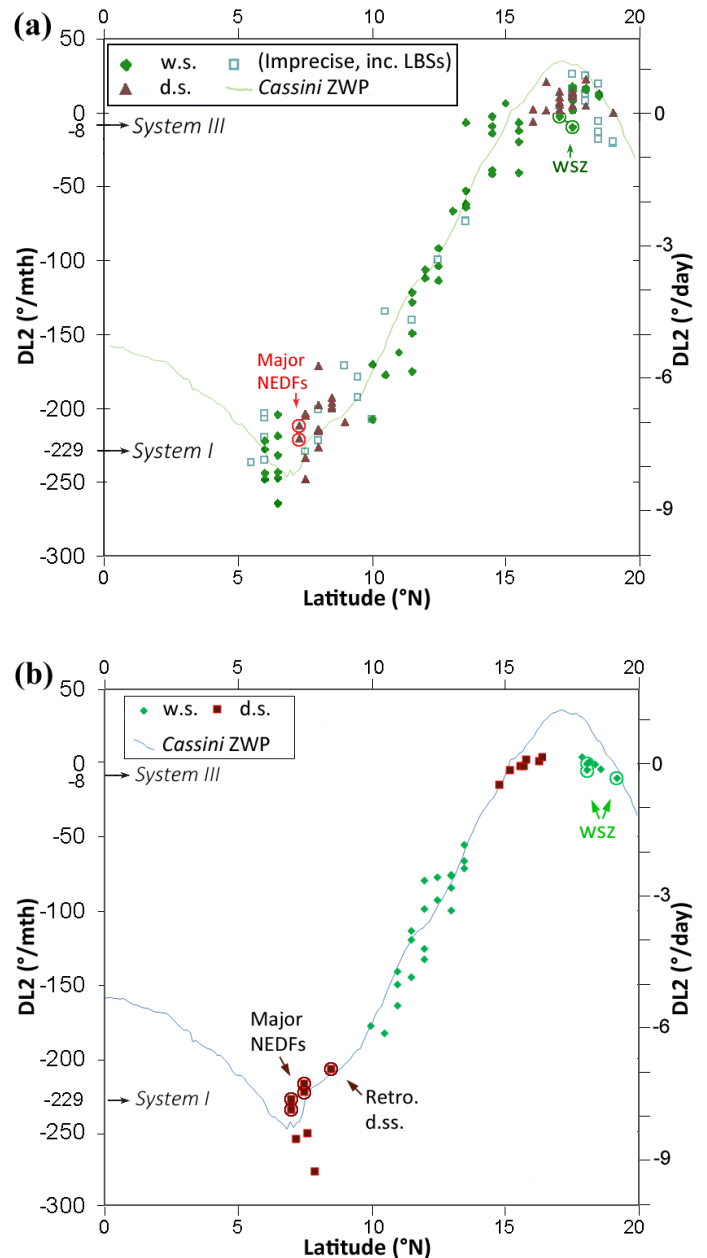
There is considerable evidence that they represent trapped Rossby waves. These are horizontal and (at this latitude) vertical meanderings of a jet, governed by the variation in the Coriolis effect with latitude, and they could be confined between the NEBs jet and the equator.<sup>10–15</sup> The true wind speed would be much greater than the phase speed of the Rossby waves (observed drift rate of the NEDFs). This was verified by the *Galileo* Probe, which showed a speed of  $\sim 170\text{m/s}$  below cloud-top level.<sup>16,17</sup>

Moreover, the phase speed should vary according to the wavelength of the Rossby waves (spacing of the NEDFs). Evidence for such a correlation has been reported (broadly agreeing with our data for recent years),<sup>12,18</sup> and we have confirmed and extended this relationship in some recent reports.<sup>19,20</sup> Detailed study of the NEDF dynamics in *Cassini* movies further supports the Rossby wave model.<sup>21</sup> The model can also describe the South Equatorial Disturbance; a large solitary wave that is sometimes present on the SEB (Figure 1).<sup>10,15,22,23</sup>

## NEB Expansion Events (NEEs) and Revivals

For most of the last century, the NEB has consistently been a major dark belt, not subject to the large-scale fadings and revivals for which the SEB is famous. However, in earlier decades, it did undergo drastic narrowings and vigorous revivals comparable to those of the SEB. Some of these NEB Revivals attracted attention at the time;<sup>24</sup> subsequent review of the literature showed that they occurred every three years from 1893–1915.<sup>1,3</sup> No more NEB Revivals occurred after 1915, except for one in 1926, but more modest narrowings and broadenings were recorded every 3–5 years from 1918–’35.

These ‘NEB expansion events’ or ‘broadening events’ (NEEs) were first described by Rogers (1995, pp.126–130).<sup>1</sup> Like NEB Revivals (but on a lesser scale), they consisted of broadening of the dark belt to the north (to  $\sim 20$ – $21^\circ\text{N}$ ), usually followed within

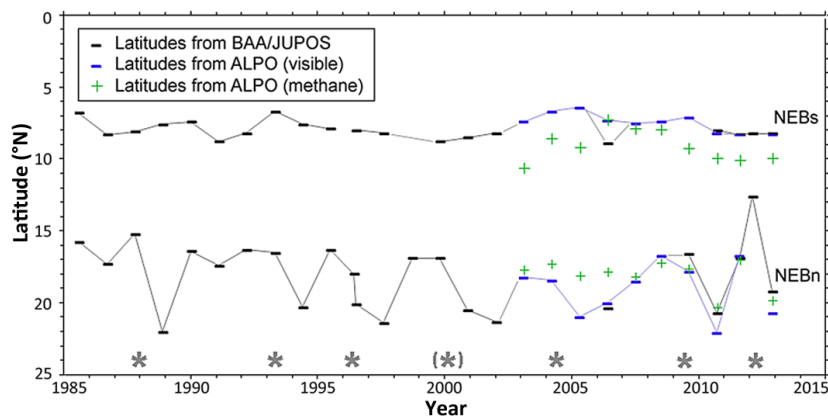


a year or so by reddening of the expanded NEB, and by the appearance of an array of barges and AWOs within the northern edge. NEB rift activity might accompany the broadening or occur later, but the visual records did not show any consistent relationship (see Footnote 1).<sup>1,3</sup>

NEEs occurred cyclically up to 1935, continuing into the 1950s though with less regularity and/or less complete documentation.<sup>1</sup> However, they did not occur at all after the 1960s, until 1987/88. The unexpected expansion of the belt in 1988 was the first in a series of such cycles<sup>26</sup> – again at intervals of 3–5 years – which have continued to the time of writing in 2016 (Figures 2 & 4).

### Footnote 1.

Major features of NEEs seem to have been noticed by A.P. Lenham,<sup>25</sup> although he did not describe them as a coherent process. He plotted the width of the NEB, giving an estimate of its redness and the mean speed of the NEDFs, from 1914–’43. He reported a rough periodicity of 3–6 years in the width, and also noted probable correlation between large width, redness and slow drift rate (long rotation period). We now know that the expanded NEB tends to have these properties within a year after a NEE starts (see this paper’s discussion on speeds of NEDFs).



**Figure 4.** Chart of latitudes of the N and S edges of the NEB over the years 1985–2012. Asterisks indicate times of onset of NEEs. Data are from the following sources: 1985–2002 (black), BAA/JUPOS apparition reports published in the *Journal of the BAA* (except 1993 & 1994 which are still unpublished); 2002–’12 (blue & green), Association of Lunar & Planetary Observers (ALPO) apparition reports published by R. W. Schmude in the *Journal of the ALPO*; 2009–’12 (black), estimates from hi-res maps produced by M. Vedovato of the JUPOS team. Green crosses are measurements from methane-band images ( $0.89\mu\text{m}$ ), in which the NEBs was often at much higher latitude than in visible images, and the NEBn sometimes did not change during visible-light NEEs.

This article covers the years from 1986–2010, in which there were six NEEs. It ends prior to the great NEB fade and revival in 2011–’12, which was an exaggerated version of a NEE that had not been seen for nearly a century; this cycle will be described in Papers II and III.

This time-span also covers the establishment of hi-res amateur imaging, which started with hi-res Kodak TP2415 film around 1985, developing further with CCD imaging in the early 1990s, and again with the introduction of webcam imaging in the early 2000s. The analysis has also been transformed, from 1998 onwards, by the JUPOS project, which systematically measures the positions of spots on images and generates detailed, comprehensive charts of their motions. Therefore, the recent activity in the NEB has been defined with far better spatial and temporal resolution than was possible in the era of visual observations.

This article will summarise the development of the six NEEs from 1987–2010, and the drift rates of the NEB rifts and NEDFs during those years. We suggest that NEEs are associated with distinctive drift rates for NEB rifts and for NEDFs, and discuss whether these are, respectively, causes and consequences of the NEE.

The results are all derived from BAA/JUPOS analysis of amateur observations, unless otherwise stated. Most of the data have already been published in the *Journal* or posted in reports on the BAA Jupiter Section website, which can be consulted for further details. The more important reports are referenced herein, and a complete list of these has been posted at: <https://www.britastro.org/node/8241>. We have not yet completed our analyses for some of the years, but preliminary data give an adequate overview. In general, data are from the following sources:

- 1986–’92 & 1995–2002: Full reports published in the *Journal*.
- 1993 & 1994: Unpublished BAA reports (M. Foulkes & J. H. Rogers) and Interim report.<sup>27</sup>
- 2002–’04: Unpublished BAA/JUPOS analysis.
- 2004–’11: BAA/JUPOS reports published on the Section website; interim reports for all apparitions and final reports for 2005–’07.<sup>20,36</sup>

## 2. NEB Expansion Events (NEEs)

A NEE (ref. 1, pp. 126–130) is characterised by broadening of the NEBn edge northwards, into the N. Tropical Zone (NTropZ).<sup>1</sup> The event may begin at a single longitude and spread around the planet, or it may start indistinctly, with irregular extension northwards from the NEB at various longitudes. We describe this in visual terms as ‘emission of dark material’, although in reality it may be propagation of cloud-free conditions by breakup, subsidence or evaporation of clouds. Often it starts with a ‘NEB outbreak’ (NEBO), *i.e.* the sudden appearance of an anticyclonic dark spot (ADS) in the NTropZ in conjunction with a new or expanding rift in the northern NEB (as described more fully in the section ‘Inception and progress of the NEBn expansion’). Figure 5 illustrates some of these NEEs, especially NEBOs; the diagram in Figure 5(a) is typical.

The NEE is typically followed, about a year after it has begun, by reddening of the belt, and by appearance of an array of cyclonic dark ovals (barges) and anticyclonic white ovals (AWOs) in the expanded northern NEB. NEEs occurred in 1987–’88, 1993, 1996, 2000, 2004, and 2009; there was a full NEB Revival in 2012.

### Chronicle of NEEs

In this section, drift rates are given as DL2 in degrees-per-month (30 days) in System II longitude.

#### 1988–’89 (NEE starting in 1988 December)

*From BAA reports in the Journal.*

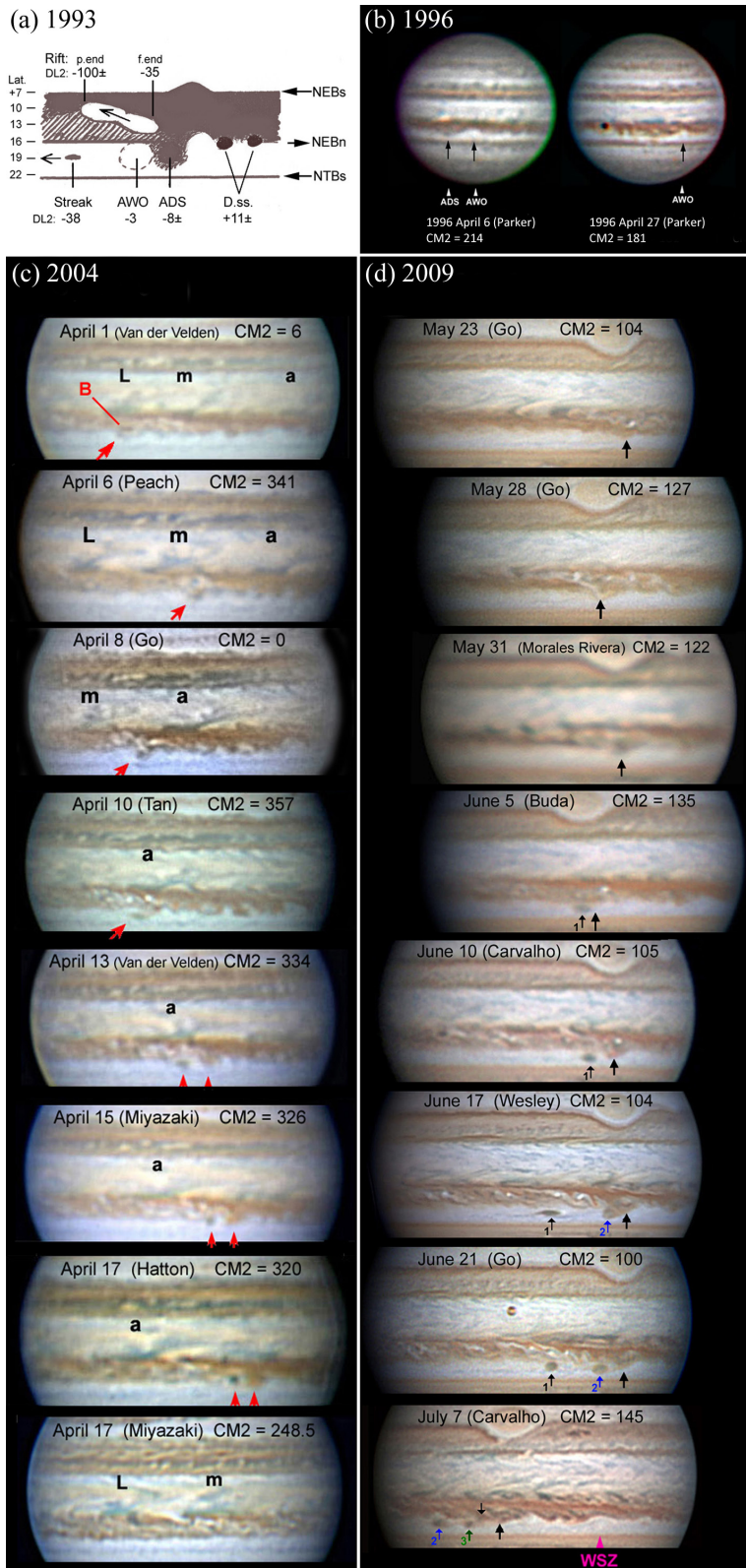
The NEE apparently began in 1987 Dec with focal disturbance (probably a NEBO) including a bright northerly rift and ADS. However the disturbance was not characterised thereafter, as solar conjunction approached. When the planet reappeared in summer 1988, the NEB had broadened impressively, and showed a pattern of small-scale mottlings without large rifts – possibly a relic of disturbance which was now active on a small scale. There was just one AWO with a barge in August; more of both developed in Oct–Dec. Then the NEBn began to fade again, in early 1989.

#### 1993 (focal NEE starting in March)

*From unpublished BAA reports and Rogers (1993).<sup>27</sup>*

In 1993, several barges and AWOs were present before the NEE. The NEE began with a NEBO on Mar 19–22 (Figure 5(a)), in which a slow-moving rift appeared suddenly and spectacularly, along with an ADS adjacent to an AWO. The ADS itself and dusky streak preceding (*p.*) it were prograding; the streak initiated a wave of transient patchy darkening of the NTropZ at DL2  $\sim -60$  to  $-90^\circ/\text{month}$ , and the ADS formed the *p.* end of a more persistent darkened (expanded) sector with DL2 =  $-35^\circ/\text{month}$ . The following (*f.*) end of the original rift was a bright white spot until May – accelerating from  $-30$  to  $-51^\circ/\text{month}$  – and probably engendered a second eruption in late April, at the original site. At other longitudes, dusky streaks streaming off NEBn dark spots contributed to the NEE. By August, the NEB was broadened into the NTropZ almost everywhere.





**Figure 5.** Images of early stages of four NEEs, including NEBOs. (a) 1993; (b) 1996; (c) 2004; (d) 2009.

(a) The NEBO at the origin of the NEE in late March, 1993, summarised from drawings and photographs. Numbers are drifts (DL2, °/mth).

(b) Origin of the NEE in 1996 April. On Apr 6 (the first image to show it) there is a newly formed ADS and bulge just *p.* an AWO. By Apr 27, a spotty expansion of NEBn has spread some way *p.* this AWO. Colour fringing of the disk and satellite shadow are due to time intervals between the colour channels.

(c) Origin of the NEE in 2004 April. On Apr 1, a NEBO beginning as an ADS (red arrow) appears adjacent to a pre-existing barge (*b*), while a large NEB rift system is passing it. New bright rifts then proliferate around this longitude. While the first ADS changes from grey to brown, a second, very dark grey ADS appears 10° *p.* it on Apr 13. Meanwhile, NEBs dark formations labelled *L*, *m*, and *a* drift past; *m* and *a* are disturbed as they pass the outbreak. The final panel shows the sector *p.* the NEBO, filled with the large pre-existing rift system.

(d) Origin of the NEE in 2009 May–June. On May 23 a brilliant white spot appears in a pre-existing rift system (arrow). By May 28, this develops into a rift pushing northwards into the NTropZ, which generates a very dark grey ADS (May 31). This is the first of three ADSs which are formed at this site and prograde (numbered arrows).

By 1994 March, there were three AWOs and two barges; other barges developed up to July. The NEBn was fading again from mid-1994.

### 1996 (focal NEE starting in 1996 April)

*From BAA reports in the Journal.*

In 1996, the NEE (Figure 5(b)) started with an ADS (first recorded on Apr 6), adjacent to a very bright AWO. A striking spotty expanded sector spread *p.* from there at  $\sim -70^\circ/\text{month}$ , though ‘not quite as flamboyant as in 1993’. There was also irregular northwards expansion of the other longitudes of the NEB, which was completely expanded by late June.

In 1997, a circum-global array of barges and AWOs was present from the earliest images in April–May. In 1997 Nov, the NEBn was receding again.

### 1999–2000 (irregular NEE developing gradually in 2000)

*From BAA reports in the Journal.*

Unusually, six barges and two AWOs were already present before and during the NEE. This NEE developed very slowly and irregularly from summer 1999 to late 2000.

A notable ADS (‘Little Brown Spot’) appeared in 1999 July. From August onwards, some dusky spots and streaks were spreading northwards from NEBn projections and at  $20^\circ\text{N}$ , but with no evident pattern and this darkening appeared to be abortive. In 2000 Jan–Feb, the dusky material largely faded away, though the NEBn barges and ADS remained. General broadening did not develop before solar conjunction in 2000.

By 2000 July, the gradual expansion event was well under way. It was complete in one  $90^\circ$  sector; the next  $70^\circ$  sector quickly darkened thereafter. The remaining sector showed an irregular NEBn, with dark projections, dusky streaks and yellowish shading, all of which developed to complete the darkening by the end of 2000.

In 2000/01 the NEB was rich brown – possibly redder than usual – and in 2001/02 it was notably reddish, while the northern EZ had weak yellowish shading. There were more barges and AWOs than before, forming a typical array. The NEBn brightened again in spring 2002.

### 2004 (NEE starting in early 2004)

*From unpublished JUPOS data & bulletins for 2002–’04 (recently re-posted for 2003–’04)<sup>30</sup> and final BAA/JUPOS reports posted online for 2005–’07.<sup>36,20</sup>*

See Figure 5(c). In early 2004, there were three successive NEBOs in early February (adjacent to White Spot Z), late February, and early April (adjacent to the only remaining barge). Each NEBO created a dark brown ADS in the NTropZ just after the *f.* end of a slowly-moving rifted region passed by. Only the third initiated general broadening, with more spots appearing *f.* it to broaden that sec-

tor by the start of May. Broadening was also starting at other longitudes in May, as the apparition ended.

In 2004/05, broadening was complete when the new apparition started in 2004 Nov, and new barges and AWOs were developing. They continued to do so up to 2005 April (along a track with  $DL2 \sim -84^\circ/\text{month}$ ). Slow rifts persisted until three years after the start of the NEB expansion event and the NEB was still broad until this time. However, after 2007 April, the NEBn edge began to recede.

### 2009 (focal NEE starting in 2009 May)

From interim BAA/JUPOS reports posted online.

In 2009 (Figure 5(d)), the NEE began with a NEBO on May 28–31 when an impressive, slow-moving rift passed a large bulge marking the former location of a barge; a new bright cloud erupted northwards from it through the bulge and generated a very dark grey ADS.

Two more ADSs later appeared from the same point, also prograding. Each ADS prograded rapidly at first, but then drifted south again and halted or reversed the drift; the first recirculated retrograding on NEBn and then was lost. By August, a bright AWO had developed *f.* two remaining ADSs, while White Spot Z (WSZ) converged on the group from the *f.* side. These four anticyclonic circulations, separated by four NEBn bulges containing barges, formed a spectacular wave-like pattern until October.

Meanwhile, a second NEBO occurred elsewhere in August, exactly like the first. Other spots developed in September. By the end of the year, the broadening event was proceeding all round the planet, partly caused by small dark spots or streaks extending into the NTropZ, and partly by general yellow-brown shading around them. Meanwhile the rift which had triggered the NEBOs expanded, until the whole NEB was turbulent.

In 2010, the event was complete. Several new barges and AWOs already existed by 2010 April, and two more barges developed in June–July. In 2011/12, the NEBn edge started to recede.

## Involvement of NEB rifts

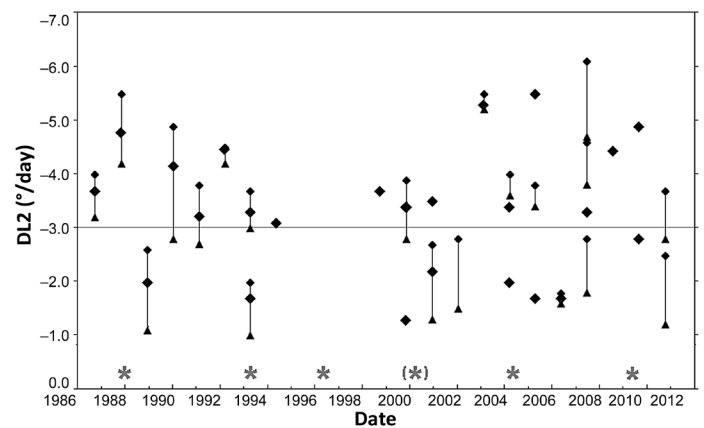
In this section, drift rates are quoted in degrees-per-day in System II. This section is adapted from Rogers (2015).<sup>29</sup>

There is often circumstantial evidence that NEB rifts are involved with a NEE or Revival, but the relationship has not been clear.<sup>3</sup> The event often begins with a bright rift – either appearing anew, or projecting a streamer northwards – which induces a dark protrusion into the NTropZ (a NEBO). Sometimes there is vigorous rift activity during the expansion event, and this is probably responsible for the effects on the NEBs dark formations (see below). However, until now it has not been possible to identify anything special about NEB rift activity in relation to NEB expansion events. Rifts are almost always present, and there is no obvious tendency for more or larger rifts during an expansion event. It would be helpful if we could quantitate the activity in NEB rifts, but this is not yet possible.<sup>29</sup>

Review of the historical record up to 1990 found that most drift rates for rifts fell into two groups. These were designated ‘North Intermediate Current’ (NIC), for which  $DL2 = -2.7$  to  $-5.0^\circ/\text{day}$  (average  $-3.9^\circ/\text{day}$ ); and ‘Fast North Tropical Current’ (up to  $-2.0^\circ/\text{day}$ ) as discussed by Rogers (1995), *pp.* 123–125.<sup>1</sup> The ‘fast NTropC’ group mainly consisted of long-lived rifted regions on the NEBn from 1973–’74 (viewed by *Pioneer 10* and *11*) and from 1977–’82 (viewed by *Voyager 1* and *2*), with  $DL2 = -0.6$  to  $-1.2^\circ/\text{day}$ . Within these, individual white spots were arising and moving much faster with NIC speeds. However, there were also several records from earlier years of visual observations in the ‘fast NTropC’ range, to which we will return in the *Discussion*. In this article, because we are considering them in comparison with other rifts,

I will refer to this range as ‘slow NIC’ rather than ‘fast NTropC’.

A survey of observations of NEB rifts from 1986–2011 showed that the speeds in these years largely fall into two ranges:<sup>29</sup> ‘fast’ with  $DL2 = -2.9$  to  $\sim -5^\circ/\text{day}$ , and ‘slow’ with  $DL2 = -1.0$  to  $-2.8^\circ/\text{day}$  (Figure 6). Thus the two speed ranges described historically are still valid, and significant for distinguishing two types of rift. Most rifts, and white spots within them, indeed move with normal NIC speeds (hereinafter termed ‘fast rifts’). However, rifts involved in NEEs are mostly more slow-moving than usual, in the slow NIC range (‘slow rifts’). Slow rifts are observed during and sometimes after an expansion event, but are absent at other times, when the NEB is neither expanding nor expanded. Although we have described the slow rifts in terms of their speed, presumably their decisive property is their northerly latitude ( $13$ – $14^\circ\text{N}$ ), of which the slow speed is a consequence. We have not identified any other visible characteristic to distinguish them from the faster rifts.



**Figure 6.** Chart of speeds measured for NEB rifts, 1986–2010,<sup>29</sup> given by large diamonds (averages or single points); small diamonds & triangles (range of observed speeds) and asterisks (dates of onset for NEB expansion events). Note that speeds are largely segregated into ranges above or below  $-2.8^\circ/\text{day}$  (BAA & JUPOS data).

From this survey, the following general conclusions emerged about the behaviour of rifts in relation to each of the five adequately observed NEEs (omitting 1996).

- 1) Fast rifts or white spots (moving with the normal NIC) can be present at any time, as even slow rifts generate internal fast spots and can accelerate up to fast speed. Fast rifts are usually, perhaps always, present when the NEE begins. However, substantial fast rifts disappear as the expansion event proceeds.
- 2) Slow rifts (moving with slow NIC; always more northerly) are not present except in relation to NEEs as described below.
- 3) Slow rifts always appear at the onset of the NEE, though usually not before. A focal NEE can be initiated at the *f.* end of a fast rift, which induces an ‘eruption’ (NEBO) – in which a slow NEB rift and a NTropZ dark spot are created simultaneously – initiating the expansion (1993, 2004 and possibly 1987–’88 & 1996; insufficient data). However, in 2009 the (moderately) slow rift arose first and then induced the NEBO. A slow rift also appeared in the early stages of the prolonged, chaotic NEE of 1999–2000. Sometimes it may appear adjacent to a barge, if any remain (1999, 2009).
- 4) During the NEE, rift activity typically evolves to smaller scales (as it also does during SEB Revivals), so within about one year



there may be only small slow rifts (1988) or no rifts at all (1994, 1997). Alternatively, slow rifts may continue to appear for just over a year (1988, 2001 & 2010) or up to three years (2004–'07), while the NEB remains broadened.

- 5) Slow rifts disappear – and fast rifts reappear – at about the time the NEBn starts to fade or recede again. Exceptions were in 2002 (when the slow rifted region remained trapped by WSZ) and 2011 (when all rifts disappeared in the run-up to the NEB Revival).

## Inception and progress of the NEBn expansion

### NEB Outbreaks (NEBOs) and Anticyclonic Dark Spots (ADSs)

A NEBO is a notable event which often defines the start of a NEE: the sudden appearance of one or more ADSs, near the *Nf* end of an active rift in the NEB. Sometimes there are multiple NEBOs, before or after the NEB expansion begins, but usually a NEBO provides the focus from which the NEE proceeds. Occasionally the rift undergoes a bright outburst, and/or emits a bright streamer rapidly northwards through a brown bulge on the NEBn, which then extends north to form the new ADS at 19°N (*e.g.* Figure 5). This has always occurred adjacent to a bay (AWO) and/or bulge (probably containing a barge), *i.e.* a pre-existing circulation on the NEBn. Even if no barge is visible, it is possible that the event always involves an inconspicuous remnant of one interacting with the rift, to accelerate the white clouds northwards. This can be seen happening (during more normal times) in the *Cassini* movies and in some of our recent observations (see *Footnote 2*).

The ADS at ~19°N may be either brown (the 'Little Brown Spot' – sometimes quite reddish) or dark grey; sometimes it is a ring with a central light spot. However, it is not methane-bright, and may be notably methane-dark. It is thus not a Little Red Spot, which would have high-altitude, methane-bright cloud cover.

Usually the ADS is initially prograding (DL2 has ranged from –3 to –62°/month), but the motion may change drastically. Often the ADSs oscillate in longitude, as recorded in 1999, 2004 (two), and 2009. We have not completed latitude analysis for these spots, but it is likely that most, if not all, such features obey the usual zonal wind profile.

I have speculated that ADSs in various domains on Jupiter, including anticyclonic vortices on jets, are shallower than other classes of ovals, which could explain why they appear not to be stably constrained to a characteristic latitude or speed.<sup>31</sup> This extends a previous conjecture (Rogers (1995),<sup>1</sup> p.260 & p.270) that the small dark anticyclonic spots on jets are shallow, whereas stable ovals and

barges extend much deeper. This model suggests that ADSs including jetstream spots are shallow vortices, comprising little air mass and fully entrained by the jets and zonal wind gradients observed at the cloud-tops (unlike AWOs and other ovals, whose motion is less sensitive to the zonal wind profile (ZWP)). This model could explain how large ADSs can be formed by clouds from 'rifts', ejected directly across the NEBn retrograding jet. These events are easier to understand if they are entirely superficial, with the retrograding jet proceeding undisturbed underneath.

The NEBn usually coincides approximately with the retrograde NEBn jet at 17.0 (±0.4)°N. Peak DL2 ranges from +25 to +49°/mth according to spacecraft data, although it is rarely detected in ground-based observations. Could NEEs involve destabilisation of the jet? There was some evidence for this in 1993 & 2004 – when chains of small dark spots were observed *f.* the NEBOs (though we did not observe full jet speeds) – and in 2009, when a short-lived feature did retrograde past White Spot Z. However, we have detected similar phenomena at other times (see *Footnote 3*), so there is no strong evidence that the NEBn jet plays an active role in the NEE.

### Progress of the expansion

The actual NEB expansion (darkening of the adjacent NTropZ) can occur in various ways, which may occur in combination.

- 1) Propagation of an expanded sector to lower longitudes (while the *f.* end remains near the original L2). This was obvious in 1993 & 1996, but even then it was not uniform nor steady. In 1993, there was a transient wave of patchy darkening of the NTropZ with DL2~ –60 to –90°/mth, but definitive darkening then spread at DL2= –35°/mth. In 1996, the leading edge had DL2~ –70 (±9)°/mth. In both years, there was also irregular northwards expansion elsewhere. In other years however, the progression was not so organised (2004 & 2009), or not observed because of solar conjunction (1988 & 2000).
- 2) Irregular emergence of dark material from the NEBn. Often this appears to include streaming *Np.* from NEBn bulges. Various streaks and patches may appear, sometimes including grey streaks prograding rapidly at 20°N with DL2= –31 to –40°/mth (1993, 1999 & 2009), which prefigure the eventual new NEBn.
- 3) Gradual darkening of sectors of NTropZ, typically starting with a yellowish colour.

In two focal NEEs, the expansion was essentially complete around the planet in five months (1993) and three months (1996) respectively. Likewise it took no more than seven months (including solar conjunction) in 1988 & 2004. In 2000, the time of onset could not be defined, but the process seems to have taken much longer.

#### Footnote 2.

Even in earlier years when no NEEs occurred, there are precedents for NEBOs where an ADS is created near the *f.* end of a rifted region.

- (i) R.B. Minton reported such events in hi-res photos in 1973 and 1974. In the 1973 event, he suggested that 'a large eddy in the NEBZ may have contributed to the rapid formation of LRS3 in the adjacent NTropZ.'<sup>32a</sup> In the 1974 event, he reported that a dark spot moved from 16.3°N to 18.7°N, just like the recent NEBOs.<sup>32b</sup>
- (ii) In the *Voyager* images (Rogers (1995), pp.120–123),<sup>1</sup> retrograding 'waves' from the NEB rifted region began to recirculate in the NTropZ when they encountered a barge, thus forming a little brown oval in the zone at 20°N. These phenomena were clearly similar to the recent NEBOs.

#### Footnote 3.

We often detect short-lived, modestly retrograding spots which are influenced by the jet. However, we only rarely detect full jet speed, and that has been mostly for spots *f.* WSZ, which evidently does perturb the jet. Those *f.* WSZ were in 1999 (DL2= +32 °/mth), 2005 & 2006 (DL2= +35 to +45°/mth) and 2009 (DL2 = +20 and +39°/mth).

## Latitudes

Latitudes of the NEBn are shown in Figure 4; the values after each NEE are listed in Table 1. The typical latitudes, compared with NEB Revivals and NEEs in previous eras,<sup>1</sup> are as follows:

| <i>Before</i> | <i>After</i> |       |
|---------------|--------------|-------|
| 1890–1916     | 11–12        | 19–21 |
| 1917–1943     | 13–14        | 20–21 |
| 1986–2010     | 16–17        | 20–21 |

Our measurements show that expansion in latitude sometimes continues even after it is apparently complete in longitude: the typical NEBn latitude is 20°N immediately after completion, but 21°N in the following apparition.

## Upper haze layer

Images in the methane absorption band at 0.89µm show haze lying just above the main cloud deck. Normally there are methane-dark belts approximately coinciding with the visible dark belts; indeed these tend to be more stable than the visible belts, possibly because the upper haze is constrained more by the fixed pattern of jets than by meteorological changes in the cloud layers. During the NEE in 2000–'01–'02, we noted that the NEB did not broaden northwards in methane images;<sup>19,33</sup> likewise it did not broaden in 2004 (Figure 4). However, it did broaden in 2009 – though not quite as much as in visible light, – and again in 2012 (Figure 4), suggesting that the NEE can sometimes disrupt the overlying haze.

Another striking feature in 2000–'01 was a regular pattern of methane-dark waves overlying the newly expanded NEB, which also coincided with thermal waves detected by the *Cassini* spacecraft.<sup>33–35</sup> Otherwise, such methane-dark waves have only been detected in a limited sector in the 2009 NEE, until now. At the time of writing (2016), a similar wave pattern has reappeared during a new NEE. Whether this is a general phenomenon is a question for further collaboration with professional astronomers.

## Later sequels

### Origin of barges and AWOs

Most or all barges and AWOs usually disappear before a NEE, except for WSZ. A new set of them develops all around the planet after the NEE is complete; a total of 12–14 such circulations is typical. The pattern can be seen from the long-term JUPOS chart from the domain, posted in Appendix I (*Supp. Online Material*).

In the best-documented cases (1988 & 2004), a few new barges and AWOs have appeared as early as 7–8 months after the onset of

**Table 1. NEB expansion events & behaviour of NEBs projections during them**

| <i>Year</i> | <i>Start date</i> | <i>Type</i> | <i>Final NEBn lat. (°)</i>     | <i>NEDFs:</i> |                      | <i>Appearance of NEDFs:</i> |                 |
|-------------|-------------------|-------------|--------------------------------|---------------|----------------------|-----------------------------|-----------------|
|             |                   |             |                                | Positive DL1? | Disrupted or fading? | New or enlarged?            | Reversed shape? |
| 1988        | 1987 Dec          | focal       | 22.0 (±0.3) (1988)             | Y             | Y                    | –                           | Y               |
| 1993        | 1993 Mar          | focal       | 20.3 (±1.2) (1994)             | (y)*          | (–)                  | (y)                         | –               |
| 1996        | 1996 Apr          | focal       | 20.1 (1996), 21.4 (1997)       | Y             | Y                    | Y                           | –               |
| 1999–2000   |                   | gradual     | 20.5 (2000/01), 21.3 (2001/02) | Y             | Y                    | –                           | Y               |
| 2004        | 2004 Apr          | gradual     | 20.4 (±0.3) (2006)             | Y             | –                    | (y)                         | –               |
| 2009        | 2009 May          | focal       | 20.7 (±0.3) (2010)             | Y             | –                    | Y                           | Y               |

Key: Y, yes; –, no. [\*Positive DL1 was recorded after the 1993 NEE but did not reach the threshold of DL1 = +7.5 defined in the section 'NEBs dark formations and the NEBs jet']

the NEE (as did one barge in 1996); then more appeared at 10–12 months. In other cases the timing was obscured by solar conjunction, but they developed within 12 months of the onset, and sometimes continued to appear up to 14–16 months (1994 & 2010).

The origin of individual circulations is almost imperceptible, as they begin very small and inconspicuous. It probably resembles the origin of barges, which has been documented more locally in the wake of a slow rifted region (1979) or of WSZ (2005 & 2006).<sup>36</sup> New small barges commonly form several tens of degrees *f.* WSZ and, in 2006, we recorded a new barge forming there by mergers of streaks retrograding in the NEBn jet.

## Reddening of the NEB

We have not attempted any systematic study of colour changes so far. Although there is a wealth of colour information in modern images, the colour balance and saturation in the images as presented is largely arbitrary, and interpretation of it is still entirely subjective. The images did generally show the NEB as unusually red in 1997 and in 2001/02, probably as sequels to the NEEs of 1996 & 2000. It is unclear whether there was any reddening after the other NEEs. Note that, conversely, the new NEBn edge is usually a narrow grey or bluish-grey band centred at 20°N.

## Clearing of the expanded NEBn

The subsequent clearing of the expanded northern NEB, by fading or southwards recession, can begin anything from 1–3 years after the onset of the NEE.

## Overview and discussion of the NEE process

It has long been thought that NEB Revivals are comparable to SEB Revivals,<sup>1,3,24</sup> in spite of major differences in the way they proceed; and that NEEs may be a similar process in which NEB rifts and NEDFs are also involved.<sup>1,3</sup> Yet until recently, it has not been possible to substantiate this conjecture.

It is notable that NEEs commonly start with the appearance of a new, brilliant white spot that becomes a rift. This enhances their similarity with comparable grand disturbances in other domains – SEB Revivals and NTB jetstream outbreaks.<sup>20</sup> However, in the SEB and NTB, this brilliant convective plume is clearly the initi-



ating feature of the disturbance, marking a source which remains coherent for many weeks. In the SEB, the plume emerges from a stationary persistent source, and in the NTB it persists on the peak of the prograde jet.

In contrast, the NEE does not always have a single source and even if it has, the new white spot does not remain there; rather, it typically drifts with the zonal wind (*i.e.*, is advected) and is sheared into an expanding rift by the wind gradient in the belt. It is worth considering whether the slow, northerly rifts are more powerful than the typical faster rifts – in terms of the energy released in them or their ability to affect neighbouring regions – however, this idea has not yet been developed quantitatively.

It therefore remains to be determined whether the plume in the NEB – the new slow rift – is a cause or effect of the initiation of the NEE. The early stages of the NEE typically include rapid protrusion of material northwards from the NEB, formation of ADS(s) in the NTropZ, as well as diffuse darkening in the NTropZ. The formation of the new slow rift – often a sudden conspicuous event – could be just one of these induced phenomena (which itself can go on to induce others), or it could be the driving force behind them.<sup>29</sup> The former option would be consistent with the apparently chaotic situation in the NEB; the latter would be more comparable to the SEB Revival.

Although we still do not have a complete understanding of NEEs, much is now coming into focus. We have identified the following components of the process and, as discussed above, the following order may – or may not – be a causal sequence.

- 1) Some unknown process causes the dark NEB to shrink in latitude, usually with a 3–5-year periodicity. This primes it for a Revival or NEE.
- 2) A rift appears which is more northerly (and hence slower-moving) than usual.
- 3) This triggers one or more local NEBn outbreak(s), propelling dark material into the NTropZ.
- 4) The darkening of the southern NTropZ (by breakup of the white cloud layer) becomes a self-propagating process, advancing to lower longitudes and/or developing diffusely, while the rift system expands across the NEB.
- 5) In at least some NEEs, a regular pattern of methane-dark waves develops in the haze over the expanding or expanded NEB.
- 6) Meanwhile, the rift system destabilises the NEBs jet, changing the pattern of NEDFs in various ways and reducing their drift rate (see below).
- 7) Turbulence in the rift systems evolves to smaller scales and normal fast rifts are suppressed, although slow rifts may persist as long as the NEB is broad.
- 8) An ‘orange flush’ may diffusely overlie the broadened NEB.
- 9) After the NEBn expansion is complete, arrays of barges and AWOs develop on either side of the NEBn jet. This may be a manifestation of a general phenomenon, that barges and AWOs are created to take up surplus energy and vorticity from the

NEBn jet – especially in the wake of a rift or of WSZ, or in the energetic aftermath of a NEE (ref 1, p.265).

### 3. Interaction of NEBs dark formations with NEB rifts and NEEs

In this section, drift rates are given as DL1, degrees-per-month (30 days) in System I.

It has long been known that NEB rifts can have notable effects on NEDFs as they pass.<sup>1,2</sup> As the rift passes, or within a few days afterwards, the NEDF may be disrupted, enlarged, or intensified; and dark patches from them may adopt positive DL1 (‘retrograding’). These effects were extensively documented from visual observations and also from *Voyager* imaging. More recently, several interactions of the same type have been described in detail from *Cassini* images (see figures 6 & 7 of Choi *et al.*, 2013).<sup>21</sup>

On various occasions, we have recorded similar interactions from hi-res amateur imaging, *e.g.*, in 2003/04 & 2005.<sup>30,36</sup> Here, I investigate whether they are involved in NEEs. This is not yet a systematic survey of the forms of NEDFs (which would be a considerable challenge, in view of all the variable parameters that could be described, and the difficulty of quantitating them). A potential relationship was apparent during the 2009 NEE, which was strikingly characterised by the sudden reappearance of the dark NEDFs after a year’s absence, their unusually slow drift rate, and the abnormal ‘reversed’ appearance of many (*i.e.* projecting at the *Sp.* instead of the *Sf.* end; *e.g.* 2009 as shown in Figure 2).<sup>37</sup> The 2009 event was observed at higher resolution than any previous example. Comparison with previous NEEs reveals that some of these phenomena do commonly occur in these events; which may be simply because NEEs always (though not exclusively) involve vigorous NEB rifts.

The behaviour of NEDFs during NEB expansion events is summarised here and in Table 1.<sup>37</sup> A more comprehensive summary of their appearances from 1986–2010 is in Appendix III (see *Supp. Online Material*).

#### 1988 (NEE started 1987 Dec)

NEDFs reappeared in late 1987 (before the NEBO), but were variable, then largely faded and in 1988/89 were small and retrograding, generally with ‘reversed’ shape.

#### 1993 (NEE started in March)

In 1993, the NEBs appearance was typical, featuring many stable projections with festoons throughout the apparition, mostly near-stationary in L1. After the NEE started, some were disrupted or swollen by rifts, and the swollen NEBs projections were modestly retrograding. In 1994, the appearance of NEDFs was still typical (though faint at some longitudes), but all had modestly retrograding drifts (mean DL1 = +5°/mth).

#### 1996 (NEE started in April)

After the NEE started, disruption/enlargement of NEDFs was noted and most NEDFs developed retrograding drifts (in contrast to 1995).

## 1999–2000

In 1999 and early 2000, NEDFs were very dark, classic projections and near-stationary. Then, gradually, they largely disappeared in late 2000. All the remaining ones were retrograding; so the transition was similar to 1988/89.

## 2004 (NEE started in April)

There was a typical array of prominent projections, but strongly retrograding from as early as 2003 Nov (DL1~ +8°/mth), and remarkably so around half the circumference from 2004 Jan–May (DL1= +14 to +21°/mth). Individual NEDFs interacted strongly with a major rift system, but this was occurring as early as January and the rift system was fast-moving. Therefore all of this occurred before the NEE, and even before the first NEBO in February.

A slow-moving rift system emerged from the large fast-moving one in early February; this triggered a NEBO which initiated the NEE in early April and, at the same time, strongly disturbed two NEDFs passing it [projections *m* and *a*; Figure 5(c)]. Further dramatic interactions continued in May, though the overall appearances of NEDFs did not systematically change; there were no ‘reversed’ aspects. In 2005 Jan there were just six long ‘plateaux’, still strongly retrograding (DL1~ +14 to +23°/mth), until they broke up in February.

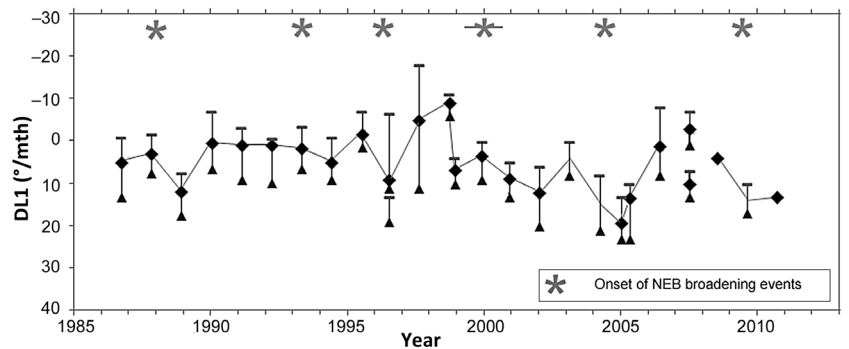
## 2009

All large NEDFs had disappeared in mid-2008 (see ‘super-fast speeds’, below). In 2009<sup>37</sup> there were few features on NEBs, apart from minor transient festoons with fast speeds (DL1~ –20 to –30°/mth), up to June. However in July, as the NEE developed, the NEBs was transformed with the appearance of many retrograding spots; induced by the expanding slow-moving rift system but spreading to all longitudes. These included small transient dark spots in the NEBs (8–10°N; DL1~ +30 to +40°/mth) and, more impressively, large plateaux (NEDFs) which developed alongside the rift system from the start of July onwards. These NEDFs were retrograding with DL1~ +10 to +17°/mth, and by September they had a spacing of 29° around most of the planet. Many of the dark plateaux/projections had ‘reversed’ tilt (e.g. Figure 2).

During each NEE, the major NEDFs showed a shift to more positive (retrograding) DL1, relative to their speeds in other years (discussed further in the next section). The changes in appearance of the NEDFs were more diverse; in different years they were disrupted, or disappeared, or enlarged. The ‘reversed’ shape of the projections was noted after the 1988 and 1999–2000 events, as in 2009, but not after others. Hence we cannot yet establish a consistent pattern of shape changes.

In summary, common aspects of the NEDFs during NEEs may be as follows: (i) positive DL1 (‘retrograding’, see below); (ii) change in appearance, becoming either more or less conspicuous; (iii) possibly ‘reversed’ shape.

Our working hypothesis now is that vigorous rifting is indeed a central component of NEEs, and that it induces diverse changes in the NEDFs globally just like the changes that have been reported during local interactions.<sup>1,2,21</sup> It is not clear whether the slow-moving rift systems associated with NEEs have any special role, or if the changes to NEDFs merely reflect the necessary presence of rifts at that time. Retrograding speed seems to be



**Figure 7.** Chart of NEDF speeds in each apparition, 1986–2010. Bars show the range of speeds observed. Only the major NEDFs are included, so the list is comparable with the historical record and does not include small features which might have different characteristics. Asterisks indicate times of onset for NEEs.

most specifically associated with NEEs, but it is instructive that in 2004, the NEDFs were already retrograding and interacting with a large rift system several months before the NEE. Whether this was coincidence, or an early aspect of the NEE process, cannot be decided at present.

In 2009, the NEE and associated rifts clearly induced the reappearance of NEDFs after a year’s absence.<sup>37</sup> Likewise, in 1893–1915, NEDFs were not normally present in this era, but new dark spots did appear on NEBs during several of the classical NEB Revivals in those years (see ref. 1, pp. 127–128). (The NEDFs had positive DL1 after the 1896 and 1906 Revivals, though not after that of 1912.) The familiar typical array of large NEDFs first became established during the 1912–13 NEB Revival. A dramatic modern instance of this would occur exactly a century later, in 2012. As we will discuss in Paper II, these events suggest that NEB rifts may actually be necessary to sustain the Rossby wave pattern that is manifest as NEDFs.

## 4. NEBs dark formations and the NEBs jet

In this section, speeds are quoted both as DL1 (degrees-per-30-days relative to System I, corresponding to the direct measurements), and as *u* (m/s relative to System III, referenced to latitude 7.0°N, which may be more convenient to accommodate the large range of eastward speeds):  $u = -(DL1 - 221) \times 0.47763$ .

### Drift rates of NEDFs

First I review the drift rates of the NEDFs since 1986. This preliminary survey is summarised in Table 2 & Figure 7. The chart follows on from the historical chart in ref. 1, p. 144–5, which showed a very slow, fluctuating decline in speed since 1913, punctuated by six marked decelerations that lasted only a year or so. It was noted that five of the six (in 1906/07, 1953/54, 1965/66, 1975/76 & 1988/89) occurred at the season of maximum solar heating of the NEB: 1–2 years after perihelion, and within one year of the greatest northerly latitude of the sun. However, the 1921 deceleration was not at this season, and other perihelia were not accompanied by decelerations. Also, it was noted that the



1906/07, 1953/54 & 1988/89 decelerations coincided with NEEs – though the others did not.

The new chart shows the mean drift was normal and stable from 1990–'95 (as were the appearances of the NEDFs), but much more variable since then (ditto). It again shows distinct decelerations, in 1988/89, 1996, 1999–2005 (especially 2004–'05) and 2009–'11. To some extent, these support the previous correlations both with perihelia (which occurred in 1987, 1999, and 2010–'11) and with NEEs (each of which coincided with a deceleration, though it was trivial in 1993, and preceded the NEE in 2004). If a mean DL1 =  $+7.5^\circ/\text{mth}$  ( $u = +102\text{m/s}$ ) is taken as the dividing line, slow speeds were associated with every NEE except (marginally) 1993. However, these correlations do not explain why the most persistent deceleration started in 1998 (just before perihelion; see *Footnote 4*) and lasted until 2006 – except that it continued the overall decline seen since 1913. The mean DL1 =  $+10^\circ/\text{mth}$  ( $u = +100.8\text{m/s}$ ) was much slower than for any other 7-year interval on record.

Nothing is known of the causes of these decelerations. The speeds of NEDFs do not depend on their latitude.<sup>36</sup> Given that a major determinant of the NEDFs' speed is their spacing (see below), it is possible that the NEE, with its associated rifting, primarily affects the spacing; perhaps by varying the power or pulsatility of transmission of energy from the convective rift systems to the wave pattern on the NEBs jet. However, in the 2009 NEE, the speed was more decelerated than the spacing would predict (see Figure 8), suggesting that the speed may be primarily affected.

While the NEDFs have developed slower drifts in recent years, they have also usually had more variable and irregular appearance. However, in 1999 and again in 2006, the NEDFs formed a more regular periodic array with faster speed (almost equal to System I), concurrently becoming much darker and more conspicuous, along with more general darkening of the Equatorial Zone (EZ). It is not clear what caused these apparently coordinated changes. In 2006 the EZ darkening seems to have been the first component of the global upheaval of 2006–'07; but in 1999 the EZ darkening was not associated with changes in other latitudes.

At other times there is a general disappearance of NEDFs and this, too, may have various causes that are not yet understood. In 2000, the number of NEDFs was reduced and a thick bright cloud layer formed over most of the EZ.<sup>33</sup> In 2008 & 2010–'12, the NEDFs disappeared from large sectors while the NEB as a whole was quiescent and narrowed, before and after the 2009 expansion event. The remarkable speeds that appeared in these NEDF-free sectors will be mentioned below and fully described in Paper II.

#### Footnote 4.

The drifts in 1998/99 are shown in the BAA/JUPOS chart [Appendix IV: *Supp. Online Material*]. In this apparition, as described in our BAA report,<sup>38</sup> the NEDFs had very variable drifts and morphologies, which often appeared to be affected by passing rifts, but seemed chaotic. In retrospect, we can see that the shift from fast to slow drifts involved two concurrent sets of NEDFs with different speeds and spacings, which overlapped for several months – as in 1997 & 2007 (see *Super-fast features, 2008–'12*).<sup>18,20</sup>

**Table 2: Our records of drifts on the NEBs/EZn, 2001–I I**

| Year        | Main NEDFs                  |                               | Rapid spots & projections: Average/Consensus (Range)         |                                      |
|-------------|-----------------------------|-------------------------------|--|--------------------------------------|
|             | No.                         | DL1 ( $^\circ/\text{mth}$ )   | DL1 ( $^\circ/\text{mth}$ )                                  | $u_3$ (m/s)                          |
| 1986–'88*   | 11 [ <i>collapsing</i> ]    | +3 to +5                      | –23 (–18 to –29)<br>( <i>p. ends</i> )                       | 116.5 (114 to 119)                   |
| 2001/02     | 4–5                         | +12                           | { –26 (–14 to –36);<br>–56                                   | 118 (112 to 123);<br>132             |
| 2002/03     | [ <i>Many (transient)</i> ] | 0 to +8 ( <i>var.</i> )       | –23 (–14 to –45)   | 116 (112 to 127)                     |
| 2003/04     | 11                          | +8 to +21                     | –18 (–12 to –35)   | 114 (111 to 122)                     |
| 2004(late)  | 6                           | +19 ( $\pm 4$ )               | –  | –                                    |
| 2005(early) | 11                          | +13 ( $\pm 2$ )               | –  | –                                    |
| 2006        | 12–13                       | +1 ( $\pm 4$ )                | –17, –28   | [ <i>w.s. in plume cores</i> ]       |
| 2007        | 12                          | { 9<br>9                      | +10 ( $\pm 2.5$ ), –21 (–17 to –37)<br>–3 ( $\pm 3.5$ ), –45 | 115.5 (114 to 123)<br>127            |
| 2008        | 3                           | +4                            | { –35 (–28 to –40)<br>–60 (–45 to –66)                       | 122 (119 to 125)<br>134 (127 to 137) |
| 2009        | 0 → 10                      | +10 to +17 ( <i>prelim.</i> ) | –27 (–18 to –40)   | 122 (118 to 125)                     |
| 2010(mid)   | 5                           | +13                           | { –40 (–30 to –49)<br>–68 (–57 to –78)                       | 125 (120 to 129)<br>138 (133 to 143) |
| 2010(late)  | 6–8                         | +13 to +39                    | –  | –                                    |
| 2011/12     | 0                           | –                             | –71 (–36 to –95)   | 139.5 (123 to 151)                   |

#### Notes:

(L) normal speeds for NEDFs; (R) fast and super-fast speeds.

This table lists all apparitions in which fast or super-fast speeds were observed. There is not a complete separation of fast and super-fast speeds; speeds in the range DL1 =  $-40$  to  $-50^\circ/\text{mth}$  can be assigned to either class. Descriptions of the appearance of NEDFs in these years, 1986–2011, are given in Appendix III (*Supp. Online Materials*).

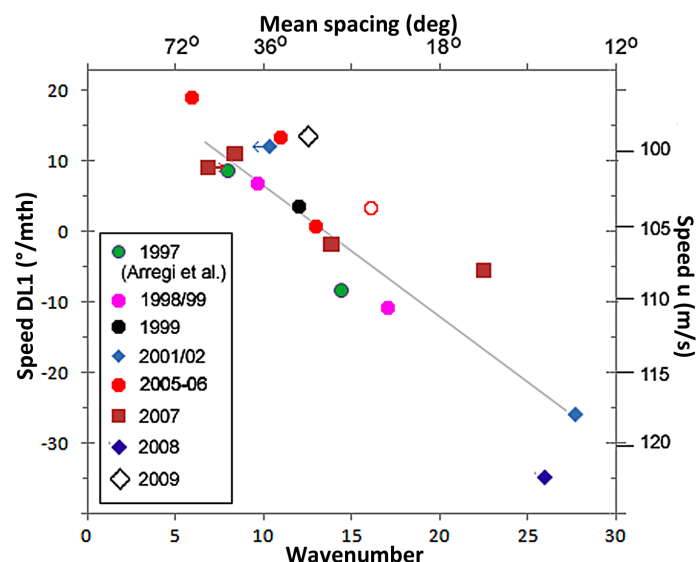
\*In 1986–'87, large dark plateaux on NEBs 'collapsed' as rifts passed, then disappeared, and their *p. ends* appeared to drift with these rapid speeds. In retrospect, these probably represented smaller rapidly-moving spots arising within the subsiding NEDFs.

## Fast-moving features ( $u \sim 120$ m/s)

Before 2001, speeds faster than  $DL1 = -20^\circ/\text{mth}$  ( $u = +115$  m/s) were rare. Nothing on the NEBs had been reported to move faster than  $DL1 = -29^\circ/\text{mth}$  ( $u = +119.4$  m/s), except for a single spot with  $DL1 = -50^\circ/\text{mth}$  ( $u = +129.4$  m/s) recorded visually, and a single record from the *Hubble Space Telescope* (HST). However in 2001/02, the JUPOS drift chart had a novel appearance.<sup>19</sup> While there were only four or five large NEDFs – which appeared as long, low plateaux – there were also numerous small spots moving exceptionally fast ( $DL1 = -14$  to  $-36^\circ/\text{mth}$ ; mean  $DL1 = -26^\circ/\text{mth}$ ,  $u = 117.9$  m/s). They were both bright spots and dark projections, typically lasting  $\sim 3$ –6 weeks. The dark spots were at  $7.6^\circ\text{N}$ , the same latitude as the normal dark formations, and they had a fairly regular spacing of  $\sim 13^\circ$  longitude.<sup>19</sup>

Similar fast-moving small spots have been seen in most apparitions since then (see Table 2), with speeds up to  $DL1 \sim -40^\circ/\text{mth}$  ( $u \sim +125$  m/s). They included similar numbers of dark and bright spots. The dark ones, miniature projections, always had a mean latitude between  $7.0$  &  $7.6^\circ\text{N}$ . The bright ones had more diverse latitudes, ranging from  $5.8^\circ\text{N}$  to  $8.2^\circ\text{N}$ . These features were usually too small to have been tracked by visual observers, so there is no reason to think they were a new phenomenon.

In 2008, a conspicuous bright rift that developed in southern NEB from May onwards, with drift intermediate between Systems I & II, led to the breakup of all the large NEBs formations in one hemisphere as it passed them during May–June. In its wake, in late May–June, one group of small short-lived features appeared with  $DL1 = -38^\circ/\text{mth}$ ; then in early July, more disrupted plateaux were replaced by a more extensive set of closely-spaced



**Figure 8.** Correlation between speed and spacing for NEDFs (from BAA/JUPOS reports), plus 1997 points (from Arregi *et al.*, 2006).<sup>18</sup> Chart updated from Rogers & Mettig (2008).<sup>20</sup> Points are only plotted for times when there were arrays of NEDFs with reasonably uniform spacing. Open symbols represent poorly-fitting values, which were for newly-created arrays of NEDFs, suggesting that the relationship may be disturbed in times of transition. This chart includes ‘fast’ but not ‘super-fast’ features.

dark projections, which soon formed an array with  $DL1$  ranging from  $-28$  to  $-40^\circ/\text{mth}$  (average  $DL1 = -35^\circ/\text{mth}$ ,  $u = +122.3$  m/s; spacing  $12$ – $18^\circ$ ).

In this sector, some of the fast-moving projections were quite large and dark. They were also dark in methane images, just like slower-moving major projections in this apparition. Therefore, they appeared to be normal projections apart from their speed. However, a sample of these that were investigated did shrink from large to medium or small size soon after they adopted their rapid drift; so we cannot be sure that such features would have been tracked in the pre-JUPOS era.

## Super-fast features, 2008–’12 ( $u \sim 140$ m/s)

In 2008 July, while large NEDFs were replaced by smaller fast projections around half the planet, the remaining large formation in another sector was replaced by even faster features, with average  $DL1 = -60^\circ/\text{mth}$  ( $u = 134$  m/s). This was faster than had been ever observed before on the NEBs.<sup>39</sup>

In spring 2009, the NEBs was still devoid of large formations and all the drifts recorded were in the fast, but not super-fast, range. This state ended dramatically in July when a vigorous expanding rift system, associated with the ongoing NEE, apparently induced the formation of many retrograding dark spots and NEDFs on NEBs. However, they did not last through the next year.

By 2010 Sep, only five major NEDFs remained – long, low plateaux – and these too were subsiding. As the NEDFs diminished, a few dark features appeared with  $DL1 = -29$  to  $-36^\circ/\text{mth}$  ( $u = 119.4$ – $122.7$  m/s) and then some much faster. In the 2011 apparition, the disappearance of the normal NEDFs resumed and the NEBs became completely taken over by super-fast speeds, which continued to accelerate until, in 2012 Jan–Feb, there was a mean  $DL1 = -83^\circ/\text{mth}$  ( $u = 145$  m/s). These unprecedented speeds will be discussed in Paper II.

**Table 3: Peak speed of the NEBs jet**

|                            | Latitude ( $^\circ$ ) | $u$ (m/s) | $DL1$ ( $^\circ/\text{mth}$ ) |
|----------------------------|-----------------------|-----------|-------------------------------|
| <i>Voyager</i> (1979)      | +5 to +8              | 103       | 5.0                           |
| <i>Hubble</i> (1995–’98)   | +5 to +8              | 105.0     | 1.0                           |
| <i>Cassini</i> (2000)      | 6.8                   | 113.9     | –17.4                         |
| <i>New Horizons</i> (2007) | 7.5                   | 112.7     | –15.2                         |
| Mean                       | 7.2                   | 108.7     | –6.7                          |
| Historical (1900–’91)      | 7                     | 107       | –3.0                          |

*Voyagers*, in 1979:<sup>40</sup> Mean  $u = 103$  m/s, the same as the NEDFs at the time. Hi-res *Voyager* images showed no systematic motions relative to the NEDFs.<sup>41</sup>

*Hubble Space Telescope* (HST), in 1995–’98:<sup>42</sup> Mean  $u = 105$  m/s. Individual charts for six dates in 1995–’98 all showed the peak in the range  $\sim 100$ – $110$  m/s, so it was always dominated by the normal NEDFs. Re-analysis reached similar conclusions, although with some points encroaching into the ‘fast’ range.<sup>43</sup> Beebe *et al.* (1996) obtained the same result in 1995 images,<sup>44</sup> but in *HST* imagery taken on 1994 July 29, they found a peak of  $150 (\pm 10)$  m/s – the only detection of super-fast speeds in *HST* images before 2008. Not included here are data from *HST* in 2008, which showed a peak speed of  $\sim 131$ – $155$  m/s over large sectors,<sup>15,45</sup> confirming our report.<sup>39</sup>

*Cassini*, in 2000 Oct–Dec: Correlation analysis found mean  $u = 114$  m/s with very high scatter ( $\pm 20$  m/s)<sup>34</sup> – probably due to a mixture of normal NEDF drifts and much faster speeds. There were only seven NEDFs, with some long gaps between them, but the EZ was largely covered in unusually thick white clouds.<sup>33</sup> Also, the near-IR images revealed widespread super-fast speeds: large sectors at  $\sim 140$ – $150$  m/s, and some up to  $\sim 170$  m/s.<sup>15,45–47</sup> The latter were mainly small white ‘scooter clouds’, possibly lying at greater depth where the *Galileo Probe* had revealed similar speed. The question of whether the super-fast speed is the true normal cloud-top wind speed will be considered in Paper II.

*New Horizons*, in 2007 Jan:<sup>48</sup> Mean  $u = 113$  m/s, *i.e.*, in the fast range – suggesting that the fast motions that we detected in limited sectors in 2007 were even more widespread at the time.



## Discussion: speeds on the NEBs jet

Determinations of the mean NEBs jet peak speed from spacecraft imaging are listed in Table 3. As explained in the footnote to that table, the speeds from *Voyager* and *HST* represent the drifts of the NEDFs at the time, and the speed from *Cassini* is probably an average between the NEDFs and the small super-fast features that were unique to that data set. The speed from *New Horizons* represents the small fast features, which we discuss below.

### Significance of the fast speeds

The fast features ( $\sim 120$  m/s) are probably common, but were usually undetectable until the advent of modern amateur imaging and analysis. They have been detected in most years since 2001, and probably also in 1986–'88.

In most of these years, they have been seen especially (though not exclusively) where the normal large NEBs projections have broken up, sometimes due to passing rifts in the NEB. But they are sometimes superimposed on the normal formations, as we reported in 2001/02 & 2007. They may co-exist with large formations more commonly, but the JUPOS measurers are less likely to separate them when the two types are superimposed. However, they seem to have been genuinely absent in years when the large NEDFs were very dark, numerous and well-organised, such as 1979 (*Voyager*), 1999 & 2006.

The shape of these features resembles the NEDFs in miniature, although this is not diagnostic of their nature because a variety of weather systems could adopt a similar shape when travelling along a jet. Nevertheless, a further reason for believing that they are similar to NEDFs is the relationship between speed and spacing. When there is a fairly regular series of these fast features, as in 2001/02 and 2008, the speeds and spacings are roughly consistent with, and extend, the relationship established for NEDFs,<sup>19</sup> as described below (also see Figure 8). In that case, their speed of  $\sim 120$  m/s is a lower limit for the true peak wind speed of the NEBs jet.

### NEDFs as planetary waves (Rossby waves)

Our records of speeds, for NEDFs and the faster features, generally reinforce the reported correlation of speed with spacing for NEDFs.<sup>12,18</sup> Our correlation line (Figure 8) is not significantly different from that of Arregi *et al.* (2006).<sup>18</sup> In our records for 2001/02, wide spacing for slow features extended the correlation to lower values of speed and wavenumber than previously obtained, while the fast features extended the correlation to higher values.<sup>19</sup> Arregi *et al.* found two separate systems in 1997 with different speeds and spacings; re-analysis of our chart for 1998 shows the same phenomenon (Appendix IV: *Supp. Online Material*). In those two apparitions, the 'zigzag' nature of some tracks suggested that the two co-existing wave systems were intersecting. This was shown even more persuasively in 2007, when there appeared to be two concurrent sets of NEDFs – one set of compact projections with zero or slightly negative DL1, and a set of longer, more widely spaced projections described as 'plateaux' with positive DL1. These behaved like intersecting wavetrains, crossing over each other and showing constructive and destructive interference.<sup>20</sup> Figure 8 shows all our results for these and some other apparitions

(only including apparitions where the spacing and speed is reasonably uniform for at least some NEDFs). Despite some scatter, this chart strongly confirms the previously proposed correlation, and thus supports the Rossby wave hypothesis.

Therefore, it is likely that the fast features are the highest-frequency members of this class of waves. The phase speed of the highest-frequency Rossby waves should converge on the actual wind speed, so extrapolation to zero spacing should give the true wind speed of the NEBs jet. Given the scatter and non-linearity of the chart, it does not give a unique value, but it suggests that this must be at least DL1  $\sim -60^\circ$ /mth ( $u \sim 134$  m/s), which is consistent with the value of  $\sim 140$  m/s inferred by Arregi *et al.*<sup>18</sup> It could even be as high as  $\sim 170$  m/s (as detected lower down by the *Galileo Probe*).

Important new evidence on the speed of the jet came in 2008–'12, as the continuing dissolution of the NEDFs led to unprecedented take-over of the NEBs by super-fast speeds of up to 150 m/s. This topic will be considered in Paper II.

**Supplementary online material is available as a PDF at <https://britastro.org/node/9140>. It consists of the following Appendices:**

- I. JUPOS chart of NEBn/NTropZ from our long-term WSZ report [from ref. 28]: [http://www.britastro.org/jupiter/2013\\_14report03.htm](http://www.britastro.org/jupiter/2013_14report03.htm)
- II. Summaries of the observations year-by-year for NEB rifts [previously posted and given as ref. 29]: <http://www.britastro.org/jupiter/relationnebrifts.htm>
- III. Summaries of the observations year-by-year for NEDFs.
- IV. JUPOS/BAA chart of NEBs formations in 1998/99.

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