Relationship of NEB rifts to NEB expansion events

John Rogers (BAA), 2015 Dec.3

Summary

Jupiter's North Equatorial Belt (NEB) shows a wide variety of impressive phenomena, but the relationships between them are still largely mysterious. Here we summarise the range of speeds shown by NEB rifts from 1986 to 2011, and consider how rifts relate to NEB expansion events, which occurred six times during those years. BAA and JUPOS records for rift speeds in those years largely fall into two ranges: 'fast' with DL2 = -2.9 to ~-5 deg/day, and 'slow' with DL2 = -1.0 to -2.8 deg/day. These confirm the two distinct ranges found in the historical record, Fast drifts are found in most years, whereas slow drifts (shown by more northerly rifts) are found only just before, during, and after a NEB expansion event. Slow rifts always appear at the onset of an expansion event, though one arose shortly before. When the expansion is completed, there may be no remaining large-scale rifts, or slow rifts may continue to appear until the NEBn recedes again. Thus a slow rift, which includes a convective plume, is always present at the start of a NEB expansion event, and could be the initiating factor, although it is also possible that the slow rift is only one among several phenomena induced by an unknown cause. This contributes to our developing view that NEB expansion events affect the whole belt and are comparable in many respects to SEB Revivals.

Introduction

Rifts are white streaks and spots within the NEB; they are turbulent cyclonic convective regions. They are often initiated or renewed by the appearance of brilliant white spots which are believed to be thunderstorms, which then 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.

There is a continuous gradient of wind speed across the NEB, as shown by zonal wind profiles (ZWPs) 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) (Fig.1). Rifts have drift rates within this range. However, review of the historical record found that most drift rates for rifts fell into two groups, designated *'North Intermediate Current' (NIC)* (DL2 = -2.7 to -5.0 deg/day, av.-3.9 deg/day) and *'Fast North Tropical Current'* (up to -2.0 deg/day) [Ref.1, pp.123-125]. (Throughout this article, speeds are quoted in degrees per day in System II; see Methods, below.) 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 deg/day, within which individual white spots were arising and moving much faster with NIC speeds. But there were also several records from earlier years of visual observations in the 'fast NTropC' range, which we will return to 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 NEB expansion event [Ref.1, pp.126-130] is characterised by broadening of the NEBn edge northwards into the N. Tropical Zone. Extreme versions of them, preceded by unusual narrowing and/or fading of the NEB, are called NEB Revivals. The event may start at a single longitude and spread around the planet, or it may start indistinctly with irregular emission of dark material northwards from the NEB at various longitudes. All these events are typically followed, about a year later, 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. NEB expansion events occurred in 1987-88, 1993, 1996, 2000, 2004, and 2009; then there was a full NEB Revival in 2012. For a summary and discussion of them, see [Ref.2].

There is often circumstantial evidence that NEB rifts are involved with the expansion event or Revival, but the relationship has not been clear. The event often begins with a bright rift either appearing anew, or projecting a streamer northwards which induces a dark protrusion into the NTropZ. Sometimes there is vigorous rift activity during the expansion event, and this is probably responsible for the effects on the NEBs dark formations [Ref.2]. In the lead-up to the 2012 NEB Revival, the narrowing of the NEB and disappearance of large NEBs formations was accompanied by, and possibly due to, an exceptional absence of rifts [Ref.3]. NEB expansions and Revivals appear to be analogous to SEB Revivals, which are essentially driven by rifts appearing at a source.

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, for various reasons. Detection of NIC drifts cannot be taken as a reliable indicator of activity, as quiescent features could have similar drifts, whereas highly active rifts might be too variable to be tracked. In the late stages of an expansion event, rifts are sometimes not visible, apparently because turbulence within the belt has evolved to smaller scales. Moreover, determination of reliable drift rates for rifts is challenging as they are so irregular and changeable. A visible rift may or may not contain small bright spots representing active convection. The detection of these spots depends on their duration, and on the resolution of observations. In any case, it is not yet possible to estimate from the visible properties of rifts how much energy is being released in them.

Here I review observations of NEB rifts from 1986 to 2011. The drift measurements are are far more sensitive and precise than those reviewed in [Ref.1], especially in the more recent years due to great improvements the quality of the observations (now, images generated by the webcam selective stacking technique) and the analysis (now, based on measurements by the JUPOS project). It turns out 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, 'fast rifts'). But rifts involved in NEB expansion events are mostly more slow-moving (and thus more northerly) 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.

Data and methods

Data are taken from our BAA and JUPOS reports, as indicated in each section below. All of these are posted on, or referenced from, our web site [http://www.britastro.org/jupiter/reports.htm], except for a few which are still unpublished.

The boundaries of rifts are usually ill-defined and variable, and spots within them are usually short-lived, so drift rates are less precise than in other regions of the planet. Here we quote them in degrees per day in System II longitude (DL2). Precision is typically estimated as ±0.1 to 0.3 deg/day.

Latitudes of rifts are not always accurately measured. The JUPOS project records latitudes for individual spots, but not for the overall extent of the rifted region. Therefore, latitudes are not systematically quoted in this article. Nevertheless, when they are extensively measured to produce zonal drift profiles (ZDPs), as in our final reports for 2003/04, 2005, 2006, and 2007 [Refs.4-6], they are generally in accord with the zonal wind profile (ZWP) (Fig.1). Thus the following relationship generally holds:

DL2 = -1.0, -2.0, -2.8; -3.0, -4.0, -5.0 deg/day;
Lat. = +14.3, 13.5, 13.0; 12.7, 11.5, 10.7 ºN (±0.8º).

Results

The speeds recorded for NEB rifts in each apparition are displayed in **Fig.2**. It is notable that they fall into two ranges: DL2 = -2.9 to ~-5 deg/day, present in most years, and -1.0 to -2.8 deg/day, present only just before, during, and after a NEB expansion event (NEE). These match the two ranges that were found in the historical record, the normal NIC and the slow NIC ('fast NTropC').

However, the speeds alone are not always informative because they may refer to a variety of different components of the rifted regions, some more significant than others. I suspect that the most important speed is for the locus where most of the convective activity is generated. Often (but perhaps not always), this seems to be at the Nf. end of the rift, and therefore has the slowest drift. Faster speeds are almost always present as the rift spreads, either for individual bright spots in the rifted region, or for its Sp. end which accelerates in the latitudinal gradient, or for the whole rifted region in its later stages. The JUPOS project does not routinely track such irregular structures as whole rifts; measurements are mostly of distinct small spots or streaks. However we have found that these measurements in recent years do reveal rift tracks as the ensemble of the small bright spots or streaks, so these have greatly improved the record.

In view of these caveats, the following narrative account, organised around each NEB expansion event (NEE), may be most useful.

1986-1992 (with NEE starting in 1988 Dec.) *(data from BAA reports in JBAA):*

In summer **1986**, there were several long rifts, and one persisted all apparition. Two that were tracked had DL2 = -3.2 to -4.0 deg/day. In **1987**, some rifts were unusually prominent (perhaps because the NEB was then narrow), and some rifts were unusually long-lived. Drifts up to 1987 Nov. were -4.2 to -5.0 deg/day. Thus all rifts had normal NIC speed prior to the NEE which apparently began in 1987 Dec. with focal disturbance including a bright northerly rift. However the origin and drift rate of this rift were unknown and the disturbance was poorly characterised, shortly before solar conjunction.

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. Rift activity was evident in small white spots appearing at 15ºN on linear tracks with slow speed, average -2.0 deg/day, but they failed to expand further. Then the NEBn began to fade again in early 1989.

In **1989/90**, rifts moving with the NIC had returned. Several were seen, the greatest of whch appeared in 1989 Sep. and expanded to 70º long; more rifts appeared on its extended track, and elsewhere, up to 1990 May. It moved with DL2 = -2.8 (f. end) to -4.4 (p. end) and white spots within it had DL2 = -4.1 to -4.9 deg/day. In **1990/91** there was again a great and complex rifted region, expanding from >20º long to ~220º long, with DL2 = -2.7 (f. end) to -3.1 to -3.8 (p. end). **In 1991/92,** again, there was a major rifted region (50-80º long); DL2 = -4.2 to -4.5 deg/day. So, throughout these three apparitions, rifts only showed normal NIC speeds.

1993-1994 (with NEE starting in 1993 March) *(data from BAA reports, unpublished):*

In 1993, prominent rifts were often observed throughout the apparition. There was one major long-lived rift up to 60º long moving with the NIC (rift A: p. end DL2 ~ -3.7 deg/day, f. end variable). A less conspicuous rifted region (rift B) sometimes preceded it. Thus, rift A was similar to those of the preceding years. In contrast, rift C appeared suddenly and spectacularly as part of the NEB outbreak (NEBO) on March 19-22 which initiated the NEE (just as the f. end of rift A was passing that longitude), and it moved more slowly. In mid-April its p. part became a separate turbulent expanding rift, with DL2 ~ -3.0 deg/day for the p. end but slower for the f. end. Meanwhile the f. end of the original rift C was a bright white spot that remained intact until May, accelerating from -1.0 to -1.7 deg/day. This white spot probably engendered a second eruption in late April at the original site, creating another bright rift (E) like rift C; and another small rift (D) tracked in June with ~ -2.0 deg/day. Rifts C and E both evolved into more complex rifted regions with spots or mottling on a smaller scale into June or July. In summary, while the pre-existing rift A moved with NIC, the new rift that appeared at the NEBO moved more slowly, as did its progeny.

In 1994, there were initially no major rifts. A prominent rift system then appeared in March, and another rift later, both with DL2 ~ -3.0 to -3.2 deg/day. Thus rift activity may have been suppressed in the aftermath of the expansion event, but recovered with NIC speed after one year. The NEBn was fading again from mid-1994.

1995-1997 (with NEE starting in 1996 April) *(data from BAA reports in JBAA, plus reference to maps from Hubble Space Telescope images [Refs.7&8]):*

In 1995, the NEB was quiet with few rifts and no reliable drifts were obtained (though the HST map in 1995 Oct. showed a prominent rift). **In 1996**, the NEE started focally in early April. There were many bright rifts throughout, but observations and photographs were infrequent due to the planet's southern declination, so no rifts were tracked. The HST map in 1996 Oct. showed extensive turbulence on a very small scale, suggesting that again the physical scale of activity in the disturbance had become smaller and large-scale rifting ceased to occur. **In 1997**, there were no rifts at all in the expanded NEB; this was still the case in the HST map in 1997 Nov., even as the NEBn was receding again.

1998-2002 (with NEE developing gradually in 2000) *(data from BAA reports in JBAA).*

In 1998/99, the were two conspicuous rifted regions, one of them moving with DL2 = -3.7 deg/day. **In 1999/2000**, whole rifts were not tracked but single white spots within them moved with the normal NIC (DL2 = -2.8 to -3.9, av.-3.4 deg/day). In addition, one northerly and slow-moving rift appeared as a very bright spot alongside a barge in 1999 Nov, and then elongated: DL2 = -1.3 in Dec-Jan. Already from 1999 Aug. onwards, some dusky spots and streaks were spreading northwards from NEBn projections but with no evident pattern, and general broadening did not develop before solar conjunction in 2000. **In 2000/01**, with the gradual expansion event well under way, two rifted regions moved slowly (DL2 ~ -2.2 deg/day for both, range -1.3 to -2.7 deg/day for one), while single white spots within them had DL2 = -3.5 deg/day.

In 2001/02, there was the unusual situation of a trapped rifted region, for the first time in many years. This rifted region (at 15ºN) was trapped between white spot Z and a barge f. it, so it moved with DL2 = -0.2 deg/day, accelerating to -0.6 deg/day. Conspicuous white rifts were arising in it, including three major volleys of prograding rifts which 'escaped' past white spot Z with DL2 ~ -1.5 to -2.8 deg/day (at 11-14ºN). So on this occasion, rift activity had not been suppressed after the NEE, but continued with northerly, slow-moving rifts; even as the NEBn brightened again in spring 2002.

2002-2007 (with NEE starting in early 2004) *(from unpublished JUPOS data & bulletins for 2002-2004, and final BAA/JUPOS reports posted on-line for 2005-2007 [Refs.4-6]).*

In 2002/03, images showed no major rifts, just a few small, very bright spots in the southern NEB with DL2 ~ -5.2 to -5.5 deg/day: even faster than the usual NIC. There were also rare tiny southerly rifts that may have been derived from them.

In 2003/04 there was a long, well-defined rifted region (A), moving with DL2 = -3.4 deg/day. Its source and f. end was at 13ºN, and bright spots were probably streaming Sp. and accelerating within the rift; so this was a typical NIC rift; the JUPOS chart [Chart J10 in Ref.5] showed it containing many individual white spot tracks with DL2 = -3.6 to -4.0 deg/day. The NEE began with several NEBn outbreaks (NEBO's), viz. the appearance of 3 dark brown anticyclonic spots in the NTropZ in sequence from 2004 Feb. to early April, just after the f. end of the rifted region A passed by in each case. But Chart J10 also showed that in March, a new, slower, more northerly rifted region (B) developed from the former f. end of region A, with DL2 = -2.0 deg/day, and this was the trigger for the NEBO in early April, in which a bright new rift and a little dark spot in NTropZ appeared together.

In early 2005, several rifts containing turbulent white spots appeared at various longitudes. The first may well have been the same slow rifted region B from early 2004, with DL2 ~ -1.7 deg/day since then; three others originated in early 2005 with similar DL2. These were all mainly at 13-14ºN, although white spots from them were spreading Nf. and Sp. Each of them generated white spots drifting p. at DL2 ~ -3.4 to -3.8 deg/day, at 11-13ºN, and the track of each rifted region as a whole eventually accelerated up to this speed range. This may indicate that the waning source regions decayed until only short-lived, fast-moving spots are left. Some of them produced even faster-moving white spots with DL2 ~ -5 to -6 deg/day at 10-11ºN.

In 2006, although rifts were still present, they did not give extensive tracks on the JUPOS Chart J10 [Ref.5]; short tracks all had DL2 ~ -1.6 to -1.8 deg/day, at 13.7ºN. **In 2007,** the NEB was exceptionally disturbed, with extensive rift activity. A long rifted region from 2006 seems to have evolved into the main rifted region of 2007, which was ~80º long up to April, plus smaller ones f. it. This group had DL2 ~ -1.8 to -2.8 deg/day, with faster spots emerging from its p. end with DL2 = -3.3 deg/day. Thus, slow rifts persisted until three years after the start of the NEB expansion event – and the NEB was still broad until this time. But after 2007 April, as the main rifted region spread to affect the entire width of the belt, and the NEBn edge began to recede, further rifts proliferated. New, faster-moving ones appeared, which tended to be initiated by a bright white spot in southern NEB which then expanded into a longer rift. Separate rifts had DL2 ~ -3.8 to -4.6 (typical NIC), and included short-lived, faster rifts within them, DL2 = -4.7 to -6.1 deg/day.

2008-2010 (with NEE starting in 2009 May) *(from interim BAA/JUPOS reports posted on-line).*

In 2008, a rift had DL2 = -4.4 deg/day. **In 2009**, [Ref.2], two rifts before the NEBn outbreaks had DL2 ~ -4.9 deg/day, but another new rift, which initiated the NEBn outbreaks and expanded to almost encircle the belt, had DL2 = -2.8 deg/day. So the speeds were faster than in 2003-2005, but likewise, the NEE was initiated by a new rift which was more northerly and slow-moving than the others. The NEE began with a NEBO in late May when the impressive, slow-moving rift passed the location of a barge; a new bright cloud erupted northwards from it, and generated a very dark spot in the NTropZ. Two more spots later appeared from the same point, and a second such NEBO occurred in the same way in August. The two outbreak sources continued to develop, and the broadening event was proceeding all round the planet by the end of the year.

In 2010, there were many such slow-moving northerly rifted regions, with DL2 ~ -1.2 to -2.5 deg/day (and there may well have been faster speeds within them). They often appeared or revived with a small bright white spot adjacent to a barge, or even within one (as in the SEB Revival). Each rifted region then accelerated to ~-2.8 to -3.7 deg/day as it expanded and dissipated. All this behaviour was just as in 2005, likewise a year after the NEE. The NEB was still broad up to early 2011.

In 2011/12, the whole NEB was very quiet and the NEBn edge started to recede. There was just one small southerly rift in 2012 July, and none at all thereafter, as the NEBn recession proceeded to an exceptional degree.

Earlier years

In the historical record [ref.1 p.124], before the 1970s, the normal NIC was detected for rifts in 9 apparitions from 1927 onwards; but speeds in the 'slow NIC' range from -1.3 to -2.0 deg/day were detected in only 4 apparitions, always for white spots. These were as follows.

1927/28 [BAA Memoir]: The last classical NEB Revival had occurred in **1926** June-July. In **1927/28**, the NEB was still broadening (and very red), and there was also intense disturbance in mid-NEB; the numerous and beautiful rifts revealed the NIC for the first time, with a continuous range of speeds from DL2 = -1.4 to -4.8 deg/day (N = 12 spots, although only 6 were well tracked, in autumn 1927). So these speeds encompassed both slow NIC and normal NIC, consistent with our findings a year after an expansion event.

1931/32 and 1932/33 [BAA Memoirs]: **In 1931/32** there was a general increase in width, redness and disturbance all accross the NEB, and an array of white and dark NEBn spots, indicating that a NEE had occurred within the previous year. White spots in the NEB had DL2 = -1.4 to -1.9 (N=4). All this persisted **in 1932/33**, when internal activity was decreasing, but a white spot with DL2 = -2.0 was recorded. So again, the slow NIC was recorded for white spots in the aftermath of a NEE.

1949 [ALPO]: No further information is available.

Discussion and Conclusions

Summary of the phenomena

From the foregoing summary, we can make the following general statements about the behaviour of rifts in relation to each of the 5 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. But 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. Focal events 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 NEE (1993, 2004) (& possibly 1987-88 and 1996; insufficient data); whereas 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 appears 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 3 years (2004-2007), 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 in 2011, when all rifts disappeared in the run-up to the NEB Revival.)

Physical significance

These results contribute to our developing picture of the NEE as a large-scale process not limited to the NEBn, but affecting the whole belt, including rifts within the NEB, and changes to the dark formations on the NEBs [ref.2].

Although we have described the slow rifts in terms of their speed, presumably their decisive property is their northerly latitude (13-14ºN), of which the slow speed is a consequence. We have not identified any other visible characteristic to distinguish them from the faster rifts. In all these rifts, the bright white spots are thought to be convective plumes arising by moist convection from the deep water-cloud layer. They are almost certainly thunderstorms, as observed in the NEB rifted region by Voyager [Ref.9, & references therein], and in the SEB by Galileo [Ref.10], and in similar cyclonic turbulent regions elsewhere in the planet by Voyager and Cassini [e.g. Ref.11].

It is notable that NEEs commonly start with appearance of a new, brilliant plume which becomes a rift. This enhances their similarity with comparable grand disturbances in other domains – SEB Revivals and NTB Revivals [ref. our 2007 final report Part I]. But in the SEB and NTB, this brilliant plume is clearly the initiating 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 does, the new plume does not remain there; rather, it is advected and sheared into a rift by the wind gradient in the belt, which may be why it does not persist as a single brilliant spot.

We assume that a NEE is preceded by some unknown meteorological condition which primes the NEB to undergo this transformation (on a 3-5-year cycle). Observations suggest that even before the slow rift appears, limited projections of dark material can occur, triggered by the Nf. end of a fast rift – but this may itself be equivalent to a northerly slow rift, only weaker, and the decisive slow rift can arise from it (as in 2004).

So it 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 little brown oval(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 could be the driving force behind them. The former option would be consistent with the apparently chaotic situation in the NEB; the latter would be more comparable to the SEB Revival, where a fixed deep source, producing a series of brilliant plumes, appears to generate all the divergent phenomena.

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. This idea cannot yet be developed quantitatively, for reasons mentioned above. The more northerly rifts may be more coherent from being less sheared than normal rifts (although this is not obvious from the ZWP: Fig.1). They are evidently in a latitude where they are better placed to influence the NEBn. But future research also needs to examine whether they also have a greater influence on the NEBs than typical rifts, given that NEBs dark formations are sometimes affected during a NEE. The slow rifted region in the 1970s was affecting the NEBs formations, even when it was quite small and northerly [Ref.1 pp. 139-141]. Our reports covering recent years contain many references to rifts affecting NEBs formations or not, and a thorough review might distinguish whether such interactions depend on the type of rift involved.

In conclusion, this survey has shown that slow, northerly rifts, containing convective plumes, always appear at the onset of NEB expansion events, and may be the immediate cause of at least some of the phenomena therein. This contributes to our developing view that NEB expansion events affect the whole belt and are comparable in many respects to SEB Revivals.

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Footnote: This analysis was begun in 2015 Feb., when we were inspecting the JUPOS charts for 2004 while producing our (belated) report on the 2005 and 2006 apparitions. It was then apparent that the 2004 NEB outbreaks had occurred in association with a new slow-moving rift system, distinct from the pre-existing fast rifts; and a similar pattern had obtained in 2009. At the same time, charts for the current apparition showed that slow-moving rift systems had just re-appeared in autumn 2014, which raised the prospect of an imminent new NEB expansion event. The next day, an enquiry about the likely weather patterns on Jupiter over the next few years gave added urgency to the topic [Ref.12].

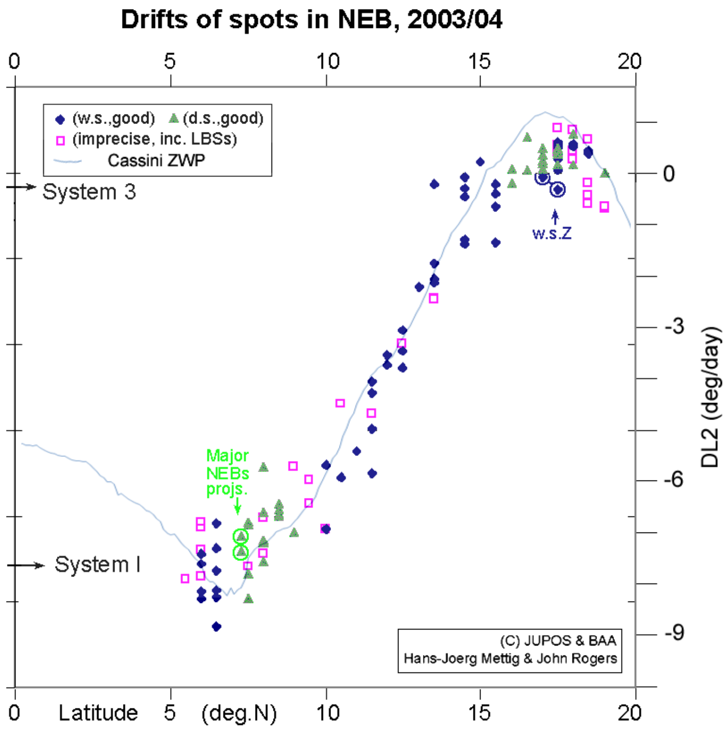

Figure 1. Zonal drift profile for the NEB in 2003/04 [from Ref.4], compared with the zonal wind profile from Cassini. Latitudes were deduced from the visibility of tracks on JUPOS charts plotted at 1-degree intervals.

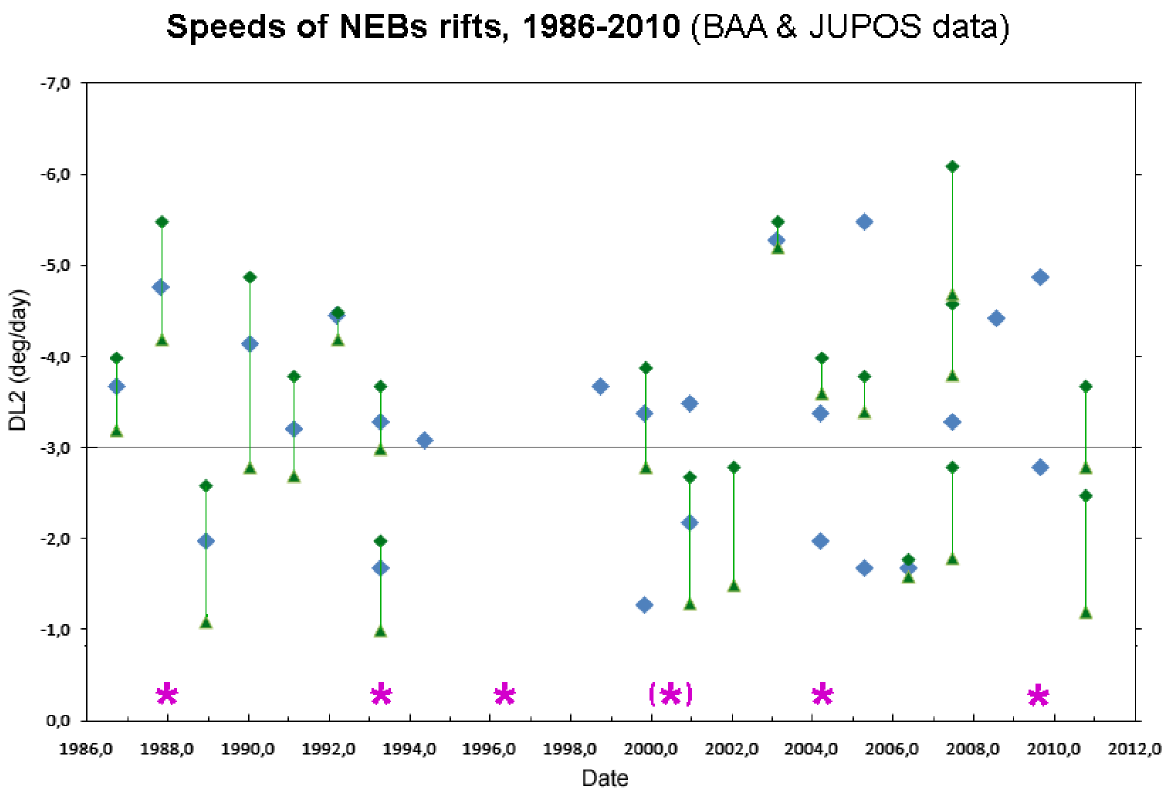

Figure 2. Speeds of NEB rifts, 1986-2010. Blue diamonds, averages or single points; green symbols, range of observed speeds; magenta asterisks, dates of onset of NEB expansion events. Note that speeds are largely segregated into ranges above or below -2.8 deg/day.