Jupiter in 2023/24, Report no.3: The major jets

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This apparition's Report no.1 described the features of Jupiter up to opposition, but only gave limited information about the variations in the major jet streams. With many superb v-hi-res images in November, and the release of a full JUPOS data set on Nov.24, we can say more about the present structures and speeds of the jets. The attached Animation-1 shows these eastward and westward wind patterns very clearly. This is a blink pair of v-hi-res images taken one rotation apart on Nov.27 – the most closely coincident of many such pairs obtained by Eric Sussenbach and Chris Go from Nov.26 to mid-Dec. Animation-2 is a similar blink obtained on 2024 Jan.10.

In this report we present the conclusions fairly briefly, but to provide a more complete picture for the reader: (i) Our previous background summaries of the major jets are reproduced as an Appendix; (ii) Our accounts from 2023/24 Report no.1 are reproduced in grey type as introductions to the conclusions herein; (iii) The JUPOS charts of the jets, and our full measurements from them, are available on request if required.

NTBs jet

Report no.1: "The NTB is virtually absent. This state could lead to another spectacular NTBs jet outbreak with consequent NTB revival; the last was in 2020. They have historically occurred at 5-year intervals, but recently the interval has shortened to 3.9 years between 2016 and 2020 [ref.1]. To predict whether there will be such an outbreak, in 2024 or 2025, or whether the series has stopped, it would be useful to know the present speed of the NTBs jet. It has been too featureless to measure from ground-based images recently, but a zonal drift profile from James Webb Space Telescope images in 2022 July has just been published [ref.2]. Although this was derived from IR images, they were probably sensing the main cloud-tops. The peak speed of the NTBs jet was $u_3 \approx 143$ m/s, which suggests that it is indeed accelerating up to another NTBs jet outbreak, which could be in 2024 or 2025."

Now, we have been able to measure the speeds of tiny features on the jet from amateur images in 2023 Oct. & Nov., all separated by one rotation (~10 hours):
--Pair of maps: images by T.Olivetti/S.Ito/I.Miyazaki (map by R. Bullen) vs S.Labergere (own map), 2023 Oct.10-12 [see Anim-1 in Report no.1], 3 data points.
--Pairs of images, E.Sussenbach vs C.Go: 2023 Nov.27 [see Anim-1 herewith], 5 points; Nov.30, one point.
The measurements are preliminary, and show considerable scatter, but give a mean speed DL1 = -3.7 (±0.8) deg/day, u_3 = 147.5 (±10.4) m/s (N=9). This is similar to last year's JWST value and confirms that the jet is approaching the super-fast state in which an outbreak can occur (Figure 1).

NEBs jet

The NEBs is very disturbed at present, with some large NEBs dark formations and many less regular, more variable features. On the JUPOS chart, the great majority of tracks have DL1 ranging from 0 to -19 deg/30d (notably faster than in recent years). There are also a few as fast as DL1 = -25, and two short tracks with DL1 ~ -44 and -40, in among the predominant, more typical tracks.

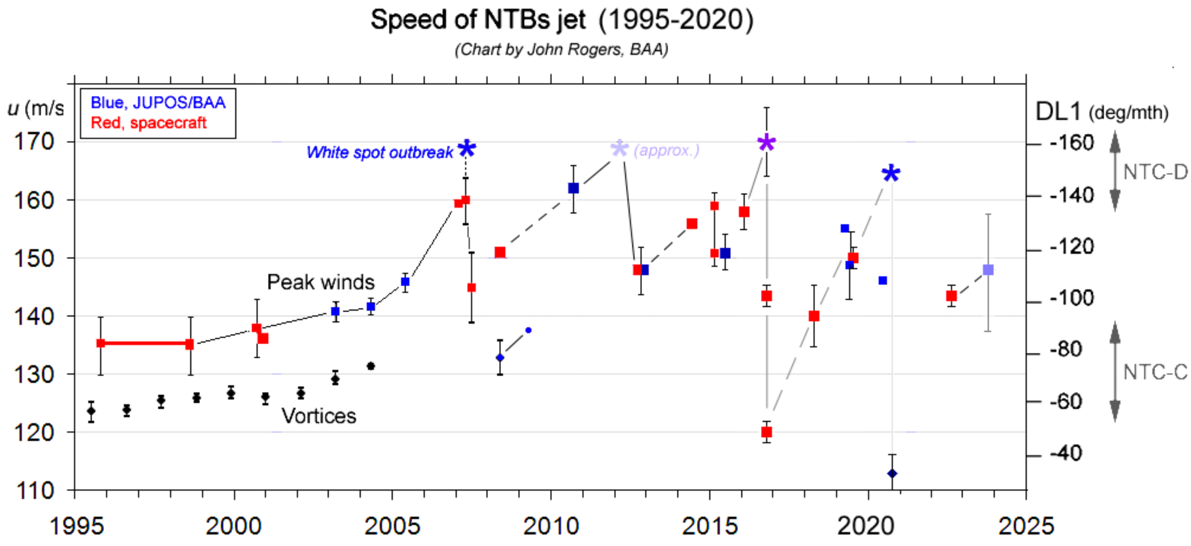

Figure 1. Speed of the NTBs jet since 1995.

Equatorial Current:
More unusual, indeed unprecedented, is the JUPOS chart representing the equator (latitudes -2 to +2ºN). While not a typical jet, there is always a velocity minimum at the equator according to ZWPs from spacecraft, with a mean DL1 = +63.0 deg/30d (u_3 = 75.9 m/s) [ref.3 on our web site.]. There are usually few if any features here that can be tracked in amateur images. But in 2023, the chart shows many short tracks, at many longitudes, with mean DL1 = +94 deg/30d (±13; N=8) [u_3 = 61 (±13) m/s] – much slower than previously recorded. They represent sparse, small, dark grey spots or streaks on the equator, mostly lasting only 4-6 days. Examples examined were dark in methane images. As there is no longer a high-altitude orange haze over the EZ, it is very likely that these spots are thinnings in the main cloud deck. Looking back at the charts for 2021 and 2022, there were a handful of similar tracks, but not so well-defined, not so numerous, and not so slow.

SEBn jet

Report no.1: "The JUPOS chart of the SEBn (not shown here) shows that most of the numerous chevrons have speeds of DL1 ≈ -34 to -54 deg/30d at all longitudes, similar to the range in the last two years. There is still a short gap, indicating that the putative S. Equatorial Disturbance (SED) is still present, with DL1 ≈ +30 deg/30d, as last year. However, in images it has no distinctive structure apart from the lack of chevrons – except since Oct.28 when Miyazaki's images show a small but typical SED rift structure."

The latest JUPOS chart shows that even faster speeds have developed. A small cluster appeared in late August with DL1 = -64 deg/30d, ~150º f. the SED, and as this travelled towards the SED, more such tracks appeared within ~120 º f. the SED, until almost all tracks in this sector were fast. Figure 2A is a chart of speed measurements for individual chevrons, grouped by month and by longitude sector, and it indicates that the fast speeds were a distinct class, faster than -60; they had mean DL1 = -75.1 (±6.7; N=17). The slower speeds persisted in other sectors, and through the whole period from July to early Nov. they had mean DL1 = -38.4 (±10.3; N=26). The tracks were distinct, with no sign of individual chevrons accelerating.

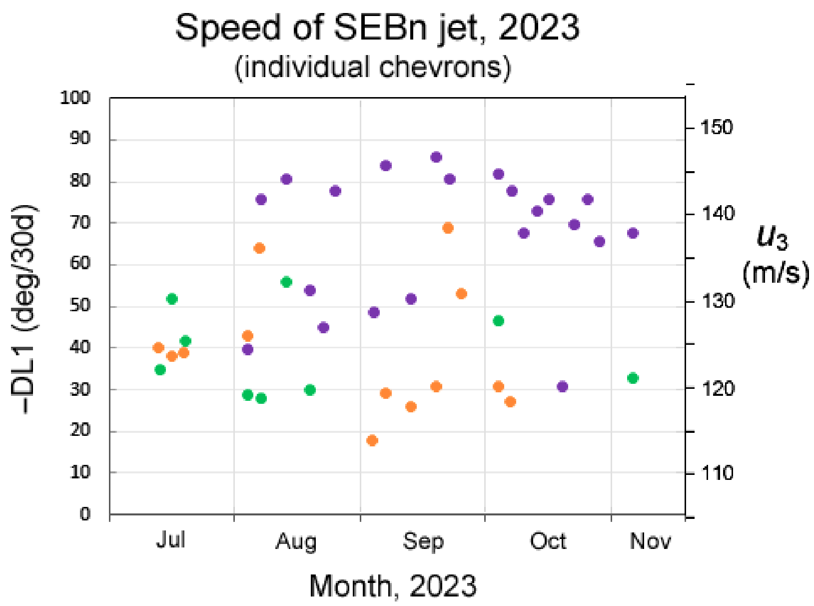

Figure 2A. Speeds of individual chevrons (-DL1, deg/30d) vs month of 2023.
Dark blue, 240-340 deg.p.SED; Brown, 120-240 deg.p.SED; Green, 20-120 deg.p.SED.

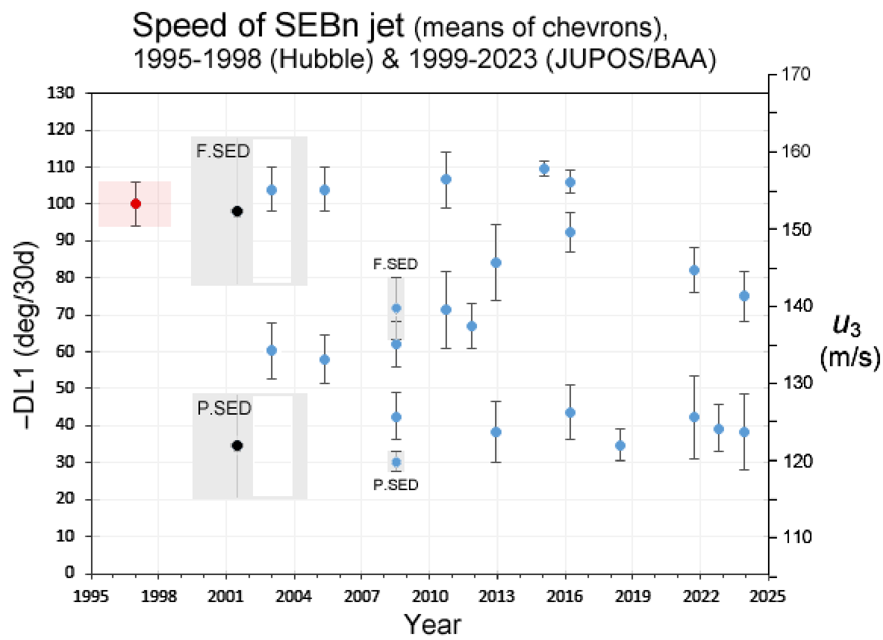

Figure 2B. Chart of the mean speeds of the SEBn (-DL1, deg/30d). Red point & shading, 1995-98, is the mean speed from Hubble data [refs.3 & 5] Grey shading, 1999-2004, shows mean speeds p. & f. the SED from our data [ref.4] , and the points for 2008 show the entire gradient relative to the SED [ref.5]. In 2003, 2005, and later years, the SED was weak or absent and the points are mean JUPOS values from apparitions that we have so far analysed.

So in Oct., speeds of chevrons were mostly fast just f. the SED, but slower elsewhere. This speed segregation was typical when there was a strong SED in some years from 1999 to 2008 [refs.4&5], and supports the case that the present feature is similar. However, there are two notable differences: the present SED looks so weak that in the 2000s it would not have affected the jet speed (indeed, whether it has persisted since Oct. is unclear), and the present jet speeds are all much less than the previous mean jet speed when undisturbed (DL1 ~ -104).

This is not the place for a complete review of variations in the speed of this jet, but we note that it adds to evidence for a discontinuous distribution of speeds on this jet, even though the chevrons are indistinguishable. The records from 1979 to 2010, from spacecraft and from JUPOS data, are briefly summarised in the **Appendix**. The mean SEBn speeds from our reports in these and subsequent years, measured by the JUPOS team (though still incomplete), are shown in Figure 2B. Grey shading indicates the range of speeds recorded p.and f. the SED when it was strong, in some years from 1999-2008. Since then, there has been no strong or persistent SED. However in 2011/12 and 2018 and 2022, there was a slow-moving chevron-free band with speed typical of a SED (DL1 ~ +23 to +30 deg/30d) – though no speed gradient -- and in 2012/13 there was a short-lived SED, with a speed gradient p. it, but it did not persist until the next apparition.

This preliminary compilation of data suggests several conclusions of interest:
-- Although there has been no strong SED since 2008, in some years there is a slow-moving chevron-free band with the same slow drift rate, possibly a similar wave phenomenon that does not produce a visible disturbance nor a speed gradient.
--Since 2016, the previously consistent rapid speed has not been present; apparently similar chevrons move with slower speeds.
--The speeds usually fall into distinct groups, which may be interspersed [ref.6]:
(i) DL1 ~ -100 to -115 deg/30d [u_3 ~ 150 to 160 m/s]: Consistently the predominant speed in Hubble data in the 1990s, and up to 2010 if the SED was absent or weak; sometimes applies to bands of chevrons which might have slower speeds. But not recorded since 2016.
(ii) DL1 ~ -65 to -85 [u_3 ~ 135 to 145 m/s]: These may be interspersed with faster or slower chevrons. (Previously, this was commonly the maximum speed upstream of a strong SED.)
(iii) DL1 ~ -20 to -50 [u_3 ~ 115 to 130 m/s]: The slowest range, and the predominant speed since 2018. (Previously, typical downstream of a strong SED.)

These distinct groups of speeds, and the recent disappearance of the usual peak speed range, are puzzling. We have yet to examine all the JUPOS data to check whether this is confirmed as a long-term pattern; but, clearly, there are dynamical differences between apparently identical features that trace the jet at cloud-top level. Presumably the jet is always fast below cloud-top level (like the NEBs jet, as probed by the Galileo Probe and the Juno gravity experiment). One possibility might be that variations in the main cloud layers affect the degree to which this deep jet penetrates up to the cloud-tops, where atmospheric waves give rise to small chevron-shaped disturbances that look much the same regardless of cloud structure [Ref. 5].

SEBs jet

From Report no.1: "There have been two examples of wave-trains on SEBs, similar to those we have reported in some previous apparitions with phase speeds less than the retrograding speed of the jet [ref.7]. The first was visible in hi-res images in 2023 Sep. in the sector p. the GRS, ahead of a SEBs ring, at the f. end of the dusky band in STropZ. These waves were entering the Red Spot Hollow around Sep.20. The second such wavetrain appeared from about Oct.4 onwards at lower longitudes, emerging around L2 ≈ 130 out of the turbulent region downstream of the SEB rifted region. It was unusual in its long extent (up to ~70° long.) and its high-contrast appearance. It was also conspicuous in 5-micron images from the NASA IRTF on Oct.16 (G. Bjoraker, personal communication). Its mean wavelength was 3.8° up to Oct.19, but longer (~5°) for waves emitted in late Oct.

We have measured the wavelength and phase speed for parts of the wave-train in Oct...

The wave-train seems to have stopped emerging around Oct.26, but it has continued to retrograde on the SEBs, and has grown even longer. In late Nov. it is ~120º long (Figure 20) – still with a wavelength of ~3.7º in the leading (higher-longitude) part, and ~5º in the trailing (less regular) part – and the leading edge is almost at the Red Spot Hollow."

Now, G. Adamoli has extended these data. Six wave-train sectors have been measured altogether in Oct. & Nov., and their speeds are plotted against wavelength in Figure 3. This year's values (brown) are plotted along with the values from previous years. They lie close to the relation established previously [ref.3], and extend it to shorter wavelengths, down to 3.5º.

It's remarkable how fast these short-wavelength wave-trains are retrograding. Their range is about the same as for the prominent rings on the SEBs jet (DL2 range +104 to +126 deg/30d, Sep-Nov.); but this is a coincidence. The peak jet speed is around +133; the vortices move slower because they are centred south of the jet, whereas the waves move slower because they propagate as waves (converging on the jet speed as the wavelength becomes shorter).

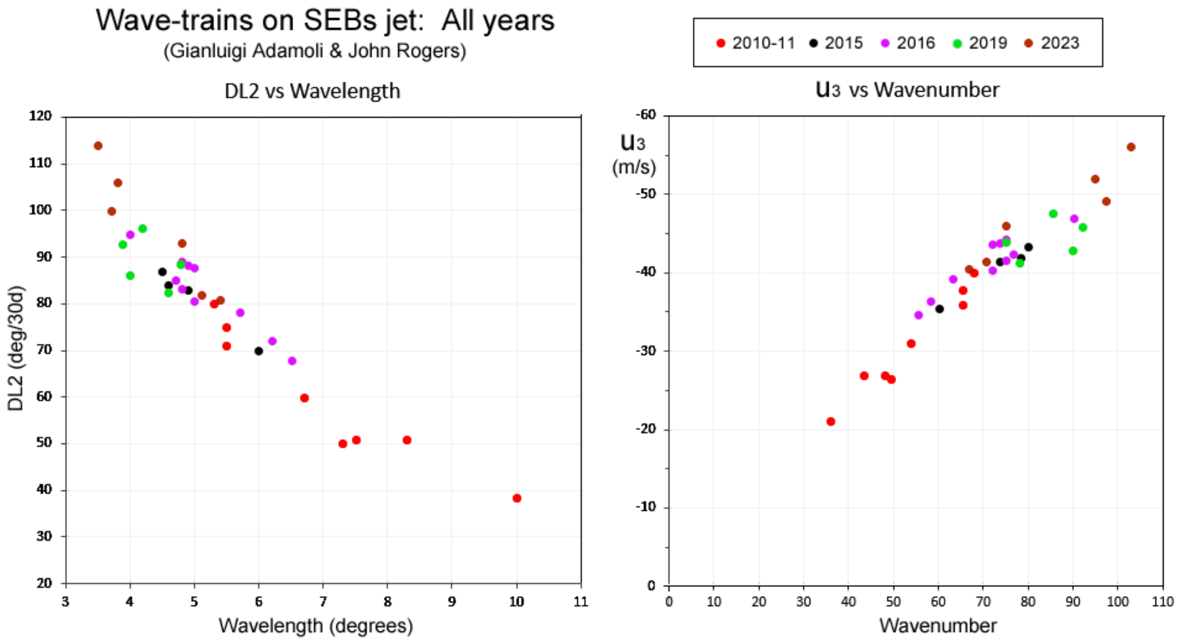

Figure 3. Drift rate versus wavelength (L) or wavenumber (R) for all our measurements of the SEBs waves. Red, 2010-11 during SEB Fade & Revival [ref.7]; black, 2015 [ref.7]; magenta, 2016 [see our 2015/16 final report, Appendix 1]; green, 2019 (previously unpublished); brown, 2023 (this report).

And finally: New understanding of the jets from Juno

Meanwhile, NASA's Juno orbiter has been fulfilling one of its prime objectives, to understand how these jets behave far below the visible cloud tops. The Juno gravity data has already shown that the main jets penetrate down ~2500-3000 km, but no further. The Juno team have now published an analysis of more data [ref.8] and conclude that the jets cannot extend downwards vertically but must be inclined to the surface parallel to the planet's rotation axis -- the first observational confirmation of the theoretical model of the jets as nested cylinders. This conclusion refers mainly to the very fast and broad NTBs jet, with minor contribution from the retrograde SEBs jet, but it seems inevitable that the other jets follow the same pattern.

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Appendix: Background data on the major jets

The account of the NTBs jet is from [Refs 1 & 10, q.v. for full references]. The accounts of other jets are from [Ref.12]. Some have been slightly edited. The STBn jet is omitted as it is not covered in this report.

NTBs jet

[from Ref.10, q.v. for full references]:

This jet has two very different states. In the 'fast' state, which held from 1991 to 2005 and in several earlier outbreaks of dark spots, it carries vortices with a speed of DL1 ~ -60 deg/30d (u_3 ~ 125 m/s, called the North Temperate Current C or NTC-C), and the peak wind speed of the jet at cloud-top level is only ~10 m/s faster. In the 'super-fast' state, which held from 1970 to 1990 and again from 2007 onwards, it undergoes spectacular outbreaks initiated by one or more brilliant white plumes at DL1 ~ -160 deg/30d (u_3 ~ 170 m/s, called the North Temperate Current D or NTC-D).

In such an outbreak chaotic dark spots appear following the super-fast plumes, leading to the development of a vivid orange NTB(S), and usually to the revival of the whole NTB. These outbreaks occurred every 5 years from 1970 to 1990 (assuming one during solar conjunction in 1985); the only previous comparable outbreak had been recorded in 1880; and they resumed in 2007. These outbreaks have been described in detail for 1975, 1990, and 2007. Each proceeded in the same way.

Usually such outbreaks occur when the NTB has faded, and lead to revival of the dark belt, so they are sometimes called 'NTB Revivals'. This is not always accurate: for example the NTB was not faint prior to the 1975 event, whereas it sometimes revived without a jet outbreak in previous decades. Nevertheless, the term has suited the phenomenon in recent decades, and is also appropriate as it resonates with the names of comparably grand Revivals of the SEB and NEB.

[from Ref.1]:

Previous outbreaks in the present series occurred in 2007, 2012, and 2016, though only the first was observed thoroughly, as the 2012 and 2016 events took place largely during solar conjunction. These were all covered in our regular reports, and there are final accounts of 2007 in [ref.9], and of 2012 with a general discussion in [ref.10], and of 2016 from a professional angle in [ref.11]. This report describes the 2020 outbreak, which was similar to the previous ones and very well observed.

[from Ref.12:]

NEBs (super-fast current):

[Ref.13 Rogers (2019) JBAA 129, 94-102 (NEB Paper II), Table 1: https://britastro.org/node/15628]

As well as the familiar NEBs dark formations (NEDFs) with small DL1, smaller NEBs features sometimes drift with a fast current (commonly) or a super-fast current (where NEDFs are absent). The super-fast range, observed for some months in 2008 and 2010 along with some slower speeds, and more completely and durably in 2011, spans DL1 ~ -45 to -95 deg/30d (u_3 ~ 127-151 m/s) [mean DL1 around -70, u_3 ~140 m/s].

SEBn:

[Refs. 4-6]

[from ref.4, R&M 2008:] All the speed measurements refer to small cloud features seen as 'chevrons', which appear to represent the peak speed of the jet. The speeds varied with longitude relative to a large wave-like feature, the South Equatorial Disturbance (SED), which drifted with DL1 = +25 to +37 deg/30d, and persisted from 1999 to 2006[2009] When the SED is present and active, as it was during the Voyager and Cassini flybys, the observed jet speed is slow p. it (~116-128 m/s, DL1 ~-22 to -47 deg/30d) but rapid f. it (~142-162 m/s, DL1 ~ -77 to -119). When the SED is absent or

weak, it no longer modulates the observed speeds: a rapid jet speed of ~155 m/s (-104) is observed at all longitudes, but some individual features move more slowly over shorter intervals.

[from ref.5, S-M et al. 2012:] In 2008 (conspicuous SED), our data showed mean speeds increasing from 120 m/s (DL1 = -30.5) p. SED to 140 m/s (-72) f. SED. In 2010 (no SED), our data showed mean speeds of 156 m/s (-107 ±8) for fast spots, 140 m/s (-71 ±10; range ~-55 to -80) for slow spots. Hubble data found ~140-160 m/s (-72 to -114) throughout. Cassini data from 2000 showed the chevrons had a true mean speed of 147 m/s (-87), while oscillating in latitude.

SEBs (retrograde):

[Refs: Rogers et al., 2016, Icarus 277, 354 (SEBs waves); Rogers, 2017, JBAA 127, 264 (SEB Rev.)]

This jet usually carries anticyclonic vortices (often distinct rings) on the S edge of the jet peak, retrograding with DL2 ranging from ~+108 to ~+133. We believe that +133 is the peak speed of the jet, although most spacecraft ZWPs give a lower value which may be dominated by the vortices themselves, and the ZDP is systematically broader than the ZWP.