Jupiter's northern hemisphere hazes as viewed by JunoCam

John Rogers (2018 Sep.10)

Report on results from the JunoCam team: J.H. Rogers (1), G. Eichstädt (2), C. J. Hansen (4), G. S. Orton (5), T.W. Momary (5), F. Tabataba-Vakili (5), M.A. Caplinger (6), M.A. Ravine (6)
(1) British Astronomical Association, London; (2) Independent scholar, Stuttgart, Germany; (3) JUPOS team; (4) Planetary Science Institute, Tucson, Arizona, USA; (5) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA; (6) Malin Space Science Systems, San Diego, California, USA.

This report covers all perijoves from PJ1 to PJ14 (except that there was no data at PJ2).
I produced a comparable report on south polar hazes up to PJ9 [Rogers, 2017 Nov.23].

Extended Summary

The JunoCam instrument on Juno takes images of Jupiter's north polar region at every perijove, usually while inbound and always while passing over the north pole, in both RGB and the methane band (889 nm, detecting reflected sunlight from high-altitude aerosols). These reveal elaborate patterns of haze bands with different characteristics in different latitude zones. In addition to the localised bands, the polar regions are covered with the well-known North and South Polar Hoods (NPH, SPH), which appear bluish (but not noticeably opaque) in JunoCam's visible-colour images, and bright in methane-band images.

The NPH appeared diffuse in ground-based methane images, until recently; but Hubble and Cassini methane images revealed multiple sharp but undulating or irregular edges, and these are now confirmed by the JunoCam maps. Table 1 lists the mean latitudes of these edges:

Table 1:

Boundaries of the main North Polar Hood								
Planetocentric latitudes and consensus wavenumbers								
Previous reports:				***JunoCam maps:***			Underlying prograde jets:	
HST	**Cassini**	**HST**	**HST**	**PJ6**	**PJ12**	**PJ12**		
UV	UV & CH4	CH4	CH4	CH4	CH4	High-phase white light		
Vincent et al.(2000)	*B-I et al.(2008)*	*B-I et al.(2008)*	*Hueso et al.(2017)*					
	64,5 or 63,7	63,3-63,8		64	63-65	64	N7	65,7
	n ~ 5	n = 8, 8, 12, 8-10		n = 8	n = 12		N6	60,7
53(±1)			55,6	52-58	50-55	51-53	N5	52,2
(variable)			n = 4-5					
				(PJ11 to PJ14:)			N4	43,6
39(±1)	46 (±2)				43-46	39-45	N3	39,0
(2018*:)								
32,5						31	N2	31,7
*From inspection of Hubble OPAL UV map in 2018.								
Wavenumbers (n) around 8-12 refer to the most common waves, omitting much longer intervals.								
Wavenumbers around 5 presumably refer to the longer intervals.								

These approximate latitudinal boundaries tend to lie near the underlying prograde jets, as listed. (Latitudes in this report are planetocentric, symbolised °Nc, unless specified as planetographic, °Ng.)

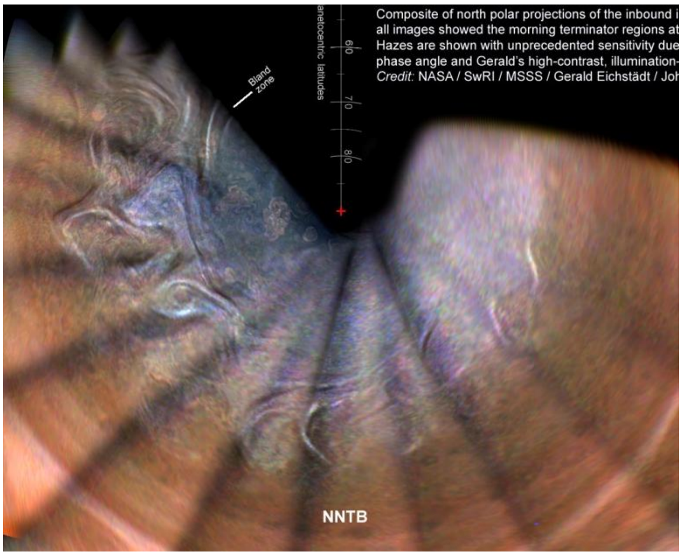
The most obvious undulations around the main NPH edge at ~64°Nc have mean wavelengths of ~30° to ~46°, both in published Hubble maps and in our JunoCam maps, but there are also some spacings almost twice as long. The undulating edge appears to be bounded by the linear bands in the bland zone (see below), which also have spacings of ~27-48° (mean 37.4°; wavenumber ~9.6), and I take this to be typical for the whole wave system.

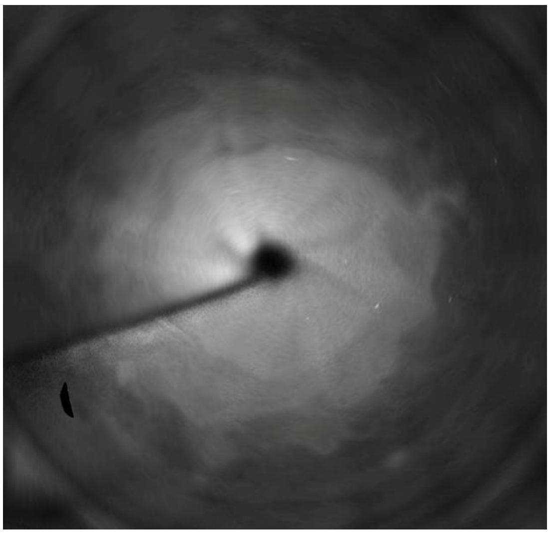
Within the NPH at >64ºNc, there are few visible haze bands. Elsewhere, in visible-colour images, there are both white and dark bands. All are seen mainly near the terminator, but dark bands are sometimes also seen under full sunlight. Some of them are also visible in methane-band images, but the relationship is complex.

The most noticeable are long linear bands in what we call the Bland Zone (a visually bland region at ~60 to 64-65ºNc, roughly lying between the two northernmost prograde jets at 61 and 66ºNc). These were seen at PJ1 [Orton et al., 2017] and are always present at most longitudes; they are slightly oblique, and often consist of adjacent white and dark (brown) bands, sometimes in bundles. The dark bands are prominent in methane images, the bright bands less so. The dark bands tend to be more conspicuous in the morning, and bright bands in the late afternoon (as also seen in the south polar region).

At lower latitudes, the images also show conspicuous bands near the terminator, often lying obliquely with inconstant relationships to the underlying zonal wind profile. A unique map from high-phase-angle colour images at PJ12 [Figures below] revealed the overall pattern. From the bundles of long linear bands in the bland zone, similarly bluish-white haze cover extends southward in huge waves and dramatic swirls. These patterns run unperturbed over tropospheric circulations, but their latitudinal boundaries appear to be influenced by the prograde jets, as also observed in methane and UV maps (Table 1 above).   I suggest that these hazes may arise from thunderstorms in the cyclonic folded filamentary regions in the N4 and N5 domains, which are also methane-bright. Alternatively, the haze may consist of aerosols created by aurorae, as the northern auroral oval extends down to ~53ºNc.

Both types sometimes run directly across anticyclonic white ovals without visible perturbation.White bands sometimes project on or over the terminator, demonstrating their high altitude. Sometimes they are bright bluish on the sunward side and reddish on the shadowed side (‘rainbow bands’). Dark bands are commonly brown; they probably include both clear lanes in the polar hoods, and shadows cast by bright bands.





PJ12 Figure N3. Northern hazes. This is a composite of Gerald's polar projection maps of the PJ12 inbound images (high phase angle and high-contrast processing). (The belt/zone contrasts are quite odd at this high phase angle.) The white features are high-altitude hazes. In Figs.N3 to N5, L3=0 is to the right.

PJ12 Figure N5. Northern hemisphere methane-band map, compiled from Gerald’s map projections of the inbound methane images.

References:

G.S. Orton, C. Hansen, M. Caplinger, M. Ravine, S. Atreya, A.P. Ingersoll, E. Jensen, T. Momary, L. Lipkaman, D. Krysak, et al. 'The first close-up images of Jupiter's polar regions: Results from the Juno mission JunoCam instrument.' GRL Vol: 44, 4599–4606 (2017). DOI:10.1002/2016GL072443

J. Rogers (2017 Nov.23), private report to JunoCam team. 'Haze bands in JunoCam's images of the south polar region.'

Methods

This report is based on north polar map projections of the JunoCam images, both in RGB and in methane, produced by Gerald Eichstädt, and merged into composite maps by John Rogers. Some misalignments between the individual maps were evident, indicating small navigational discrepancies, leading to uncertainties of perhaps a degree or so in longitudes and latitudes. In the individual maps, Gerald applied algorithms to remove the global-scale brightness variation and enhance the contrast. However, intensity and colour variations across the maps still remain, due to the wide range of emission angles and phase angles between and within images. In compositing the maps, I have tried to minimise these variations empirically to give more uniform brightness and colour across the map. Compositing the maps is done in Adobe Photoshop Elements, using the diffuse brush eraser tool to merge different maps or different regions of the same map after adjustments of brightness. There is no calibration of intensities in these maps, so features perceived in the composite maps should be checked in individual maps if there is doubt about their reality.
Indeed, any photometric calibration of JunoCam images would be difficult: in the original images, there is a possibility of scattered light, and there are colour gradients across the scan strips and across the planet's disk, traces of which still remain even after Gerald's processing.

For PJ9 and PJ12, I also made composite RGB maps giving preference to regions near the terminator, so as to show high-altitude haze patterns. PJ12 was special because on Juno's inbound trajectory it viewed the planet at higher phase angle than before, and the images (taken over several hours as the planet rotated) showed mainly the high-altitude hazes. At previous perijoves we mainly saw these near the terminator, but this map shows them completely. (Hubble and Cassini, of course, did not have adequate views near the terminator, and earlier Juno coverage did not have such high phase angle.)

In the high northern latitudes, coverage has varied significantly due to the evolution of Juno's orbit. The early perijoves allowed for good coverage inbound, and good coverage near the terminator in v-hi-res images after north pole crossing (although complete series of images were not always taken). At later perijoves, if the spacecraft was pointed at Earth and Sun (GRAV orbits), there was no inbound coverage, and the v-hi-res images after north pole crossing showed fully illuminated regions and not the terminator. However at PJ12, the spacecraft was tilted to give good inbound coverage, and due to the high phase angle (crescent view) this gave the unique perspective on the high-altitude northern hazes.

At early perijoves, Gerald did not yet have absolute longitude data, so longitudes (all in System III, L3) were established using the subsolar longitude at the time of the over-the-pole (MEA) image; these were checked by reference to ground-based tracking of long-lived white ovals, and found to be correct to within <~1.5 deg. At later perijoves, maps were projected using navigation data in L3.

Latitudes are planetocentric unless otherwise indicated. In case of doubt, I use the symbols ºNc for planetocentric latitude, ºNg for planetographic.

Background (1): jets and domains

The main tropospheric structures of the high northern latitudes are the prograde jets, whose mean latitudes are listed below (as posted on our web site and in my PJ5 report).

	Lat. graphic	Lat. centric	u3 (m/s)
N7	68,4	65,7	31,1
N6	63,8	60,7	19,6
N5	55,8	52,2	20,6
N4	47,4	43,6	21,3
N3	42,7	39,0	22,3
NNTBn	*39,3*	*35,7*	*-17,8*
N2	35,1	31,7	37,3

Table 2: Names, latitudes and speeds of jets on Jupiter
Mean values from 4 spacecraft data sets (Voyager, Cassini, Hubble, New Horizons).
Data from 'Reference list of Jupiter's jets (Rogers, 2013), posted at: http://www.britastro.org/jupiter/reference/jup_jets/ref_jets.htm
--with the addition of planetocentric latitudes.

Each pair of prograde jets bounds a domain with the same number as the jet on its low-latitude side. Within each domain (except the narrow northernmost N6, see below) there are anticyclonic white ovals (AWOs) and cyclonic folded filamentary regions (FFRs). AWOs are methane-bright *except* in the N5 domain, where they are faint or invisible in JunoCam methane images. (This may be because they are overlaid by the outer collar of the NPH.) In FFRs, the white cloud strips are generally methane-bright, both in the polar regions (Juno images**) and mid-latitude domains (Hubble images), even though they usually do not stand out as illuminated near the terminator in RGB images (although I noted some as doing so at PJ6).

> **[At all perijoves; for instance, this was noted at PJ6 and PJ11, but only at >62ºNc. This is also the case in the south polar region (SPR); perhaps it could be due to the viewing angle? But in our new PJ6 and PJ9 maps, this is also seen in the N5 and (at PJ6) N4 domains. In Hubble OPAL maps, bright streaks in FFRs are commonly methane-bright in lower-latitude domains.]

An important feature, and visual reference point, is the **'bland zone' (BZ)**, a visibly bland zone between ~60 and 64-65ºNc, contrasting with the very turbulent regions to north and south. It always contains linear haze bands. It is a permanent feature, visible in Cassini and Hubble maps although not well defined until the JunoCam images. [Mean latitudes of the edges are 59.8 (±0.9)ºNc and 64.5 (±0.7)ºNc: means of estimates from the JunoCam polar maps which are intrinsically imprecise because of its irregularity.]
It coincides approximately (but not exactly) with the N6 domain which is bounded by the N6 and N7 jets, mean latitudes 60.7 and 65.7ºNc; this is the highest-latitude domain. However, the BZ boundaries are irregular, and N5-AWOs are typically located on its southern edge [mean lat. 59.5 (±0.7)ºNc in JunoCam maps], and a longitude sector is sometimes disrupted by turbulence. [One disrupted sector, up to L3 ~ 220, was probably viewed at both PJ9 and PJ11; another at PJ10 and possibly PJ11; and a third, centred on a large N5-AWO at L3 = 129 and 66 respectively, at PJ12 and PJ14 (also seen at PJ13 but not disrupted).] We have yet to determine whether these irregularities in the BZ represent irregularities in the N6 and N7 jets.

The northern auroral oval does not match any features that we see in the JunoCam maps. It is not centred on the pole, but extends from near the north pole to ~54ºN, L3 ~ 160-170.

Background (2): Previous reports of northern hazes

High-latitude haze patterns have previously been seen in Hubble and Cassini images in methane band and UV; for instance, they can be seen in the OPAL maps from 2015 to 2018. Hubble UV images at 225 nm show high-altitude hazes as dark, largely a negative and more sensitive copy of the haze patterns (but not the tropospheric patterns) that are seen bright in the 889-nm methane band. (Only the 225-nm filter shows this; the 275-nm filter shows a more complex pattern which shows little resemblance to either.) Previous literature is as follows, although their maps had lower resolution and were taken from very oblique angles: Vincent et al.(2000); B-I et al.(2008); Hueso et al.(2017).

[These papers also cover the south polar region (SPR), in which the SPH and its wave patterns are more well-defined. The SPR alone is covered by: S-L et al.(1998) GRL 25, 4043; Li et al.(2006) Icarus 185, 416.]

1. Vincent MB et al.(2000) Icarus 143, 205-222, 'Jupiter's polar regions in the ultraviolet as imaged by HST/WFPC2: Auroral-aligned features and zonal motions.' [HST, 1994-1997, in UV (120-320 nm).]

This paper reports that the NPH is strongly UV-dark at >53 (±1)ºNc ('the NPH'), and moderately dark at 39-53 (±1)ºNc ('north polar shading'); these boundaries coincide with the known N3 and N5 jets, though few features are observed at 44ºNc (the N4 jet). The 53ºNc boundary carries large but variable waves. The 39ºN boundary is usually straight but with small wavy patterns and steps, but the shading itself is very variable with time and longitude, sometimes showing mottled or banded structure.

They particularly noted a long UV-darkened sector of the north polar shading, L3 ~ 100-260, matching the longitudes of the auroral oval, and suggested that this (like the NPH itself) represents dark hydrocarbon haze deposited from the aurorae.

They also measured zonal velocities in the UV images in 1996 June. At 39ºNc, there were weak prograde motions over the N3 jet, but from 41-60ºNc, virtually all features moved with a retrograde motion of ~-8 m/s (even at the latitudes of the tropospheric N4 and N5 jets), including features at 53ºNc which presumably represent the waves on the NPH edge. They also discussed possible meridional and vertical motions.

2. Barrado-Izagirre N, Sanchez-Lavega A, Perez-Hoyos S & Hueso R (2008) Icarus 194, 173-185: 'Jupiter's polar clouds and waves from Cassini and HST images: 1993-2006.' [In UV (258 nm, Cassini) and methane (889 nm, Cassini & HST).]

The NPH in Cassini images had distinct edges at 67.3 (±1)ºNg [64.5ºNc] (CH4) and ~50 (±2)ºNg [~46ºNc] (UV). The wavy 67.3ºNg boundary had wavenumber ~5 and phase speed (drift rate in L3) < ±5 m/s.

In HST images from 1993-2000, this 'north polar wave' was always quite irregular and less conspic-uous than the wave systems around the South Polar Hood, but in four sets of images it was always present at 66.2 to 66.7 (±0.2)ºNg [63.3 to 63.8ºNc], with wavenumbers of 8, 8, 12, and 8-10. The phase speed of the waves was measured in 1994 and 1997 and was prograding, +7 (±4) m/s [DL2 ~ -42 deg/mth] and +11 (±8) m/s [DL2 ~ -62 deg/mth] respectively (less than the underlying wind speed u_3 = +15(±5) m/s and much less than the nearby N7 jet). They did more extensive measurements and analysis of the corresponding south polar wave at 67ºSg [64ºSc], and showed that it may be a Rossby wave on the S6 jet, so presumably the north polar wave could be interpreted in the same way.

3. Hueso R et al.(2017) GRL 44, 4669-4678. 'Jupiter cloud morphology and zonal winds from ground-based observations before and during Juno's first perijove.' [inc. HST, 2016 Feb.(OPAL), 890 nm]

Both north and south polar projections show similar hazes limited at different latitudes by undulating patterns. The most conspicuous undulating pattern in the north is at ~59°Ng [55.6ºNc], and the has amplitudes of 4° with wave number N = 4–5. [However their HST methane map does not show such vast waves; it shows a mixture of large waves with wavelengths 49-64 deg, and smaller ones of 22-31 deg., similar to what we report below from JunoCam maps.]

Thus, these three papers report wavy edges to the NPH at 39ºNc, 50-56ºNc, and 64ºNc, corresponding well to the irregular edges that we report from JunoCam maps below, and approximately to the N3, N5, and N6-N7 tropospheric jets. (The 2018 HST OPAL map in UV at 225 nm actually shows fainter swirls and patches extending down to 35-37ºNg (31.5-33.5ºNc), i.e. the N2 jet, also consistent with our lowest limit from our PJ12 map.)

There is also information from ground-based infrared images, still to be analysed.

Results (1): Global patterns

Methane maps from JunoCam

Extent of maps:

We have not made north polar maps from the methane images at all early perijoves; the images were generally of low quality and noisy; however it would be worth getting a polar map of the over-the-pole methane image from each PJ if we do not already have one. Even at PJ1, Gerald's latest map of the over-the-pole methane image showed the main features. We have made composite merged maps from PJ11 onwards. I have now also made them for PJ6 (the earliest that we have) and PJ9. Note that because of the long TDI exposures and severe enhancement needed, bad-pixel streaks and scan strips are very evident in the final methane maps.

From PJ4 to PJ11, methane images were usually not available after north pole crossing, but they have been taken from PJ12 onwards

PJ6: This new north polar methane map consists of a low-resolution panel (made from the small versions of the noisy, low-quality inbound images), and a hi-res panel made from the over-the-pole images. The methane-bright NPH has a sharp wavy edge at ~64ºNc, and a fainter 'collar' down to ~52-58ºNc (i.e., over the N5 domain). (White strips in FFRs are methane-bright in the N4 and N5 domains and further north.)

PJ9: This new map has good resolution and shows good match of methane features to the linear bands in the BZ and to FFRs in the NPR and N5 domain. There is some distortion and a rotation of 0.8 deg relative to the RGB (near-terminator) map.

PJ12: This is our most complete and sensitive global north polar methane map, described below.

PJ11, PJ13, PJ14: These north polar methane maps have good quality but only cover small sectors because of the lack of inbound images; there were only the over-the-pole images and, for some, methane image(s) taken over the N5-N6 domains.

North Polar Hood (NPH)

In both the PJ6 and PJ12 methane maps, the NPH has a sharp wavy edge at ~64ºNc, with disruption at L3 ~ 330-360. (This sector does not coincide with the auroral oval.) A sharp edge at ~63-64ºNc can also be seen in small sectors of the PJ11 and PJ13 methane maps, but these were not extensive enough to give a circumglobal view. The edge at ~64ºNc lies within the BZ in the RGB map, just south of (PJ6) or at (PJ9) the boundary with the dark blue NPR. In the PJ6 hi-res panel, the bands in the methane map clearly match the bundles of bands in the BZ near the terminator.

It is difficult to give a definite wavelength for the NPH edge; individual peak-to-peak longitude intervals (at PJ6 and PJ12) range from 22º to 88º. Around the whole 360º I count 6 waves at PJ6 and 9 at PJ12, but the more distinct waves are those with shorter wavelengths, averaging 46º at PJ6 (3 waves; wavenumber 8) and 30º at PJ12 (6 waves; wavenumber 12). It seems likely (and it is evident in some parts of these maps near the terminator) that the NPH generally has a sharp edge abutting the visible brown linear bands in the BZ (mean wavenumber ~9.6; see below).

Linear bands in the Bland Zone

Here, the white bands are sometimes visible in methane images but usually not prominently methane-bright, although the brown bands are always notably methane-dark. In the new PJ9 methane map, the BZ is methane-dark, and we clearly see the linear bands as bright or dark bands, largely forming the edge of the main NPH.

Waves and swirls further south

At <60ºN, comparisons are limited because at most perijoves, methane images were not taken after the over-the-pole (MEA) image, in which the region is near the limb, and we have not yet studied it in polar map projections for many perijoves. In general, the visibly bright haze bands at <60ºN do match methane-bright features, but sometimes appear to be not exactly co-extensive with them. I think the methane images show a mixture of visibly bright haze bands, and more extensive regions of the wider NPH, and bright strips in FFRs, and the prominence of these various features probably depends on emission angle and/or phase angle. Further study of these features is warranted, from existing maps and from future perijoves.

PJ6: The methane-bright NPH has a fainter collar down to ~52-58ºNc (i.e., over the N5 domain). (White strips in FFRs are methane-bright in the N4 and N5 domains and further north.)
PJ9: The new map shows FFRs methane-bright in the N5 domain. In the N4 domain (at the edge of the map and possibly distorted), it appears that traces of FFRs are mixed with diffuse hazes, including but broader than the visible ⊃-shaped bands.
PJ12: The NPH has a moderately bright collar down to ~50-54ºNc (the N5 jet; i.e., they are over the N5 domain), with a wavy, irregular edge; and an even fainter and less regular periphery of patches and streaks down to ~45ºNc (i.e., over the N4 domain), with some even lower. The methane map has limited resolution but matches closely the hi-res high-phase-angle visible map (below).
PJ11, PJ13, PJ14: The limited sectors shown in these methane maps all show similar patterns to PJ12, with the NPH surrounded by fainter methane-bright patches or waves or swirls down to 43-46ºNc (the N4 jet). In the accompanying RGB maps, haze bands are only visible near the terminator, but they show elaborate patterns and clearly match bands shown in the methane maps. (PJ11: The methane map (Fig.3) is unusually informative. It shows the visibly bright haze bands in the N4, N5 & N6 domains as methane-bright, and also a notable methane-bright 'blob' at 44ºN, which maps not to an AWO, but to a complex cyclonic region partially overlapping a FFR—suggesting that this is a transient feature of the overlying haze layer.)

Methane maps from amateur ground-based images

The main outlines of these haze features can now be detected in the best amateur methane-band images. PJ12 Figure N6 compared the JunoCam maps with polar projection maps from images taken by Chris Go on April 1, the day of Juno's PJ12. The multiple edges of the N. Polar Hood revealed by JunoCam were also recorded in Go's image, along with some of the methane-bright waves and patches.

Maps showing haze bands in visible light near the terminator from JunoCam

Extent of maps:

From the start, JunoCam images have shown haze bands near the terminator. We have not made many north polar projection maps highlighting the terminator region, as the coverage is often sparse. For **PJ4,** I made a preliminary global cylindrical map of near-terminator hazes , but a polar map should be done. At **PJ9,** we made our first extensive north polar projection map blended so as to select the near-terminator regions. However, the global patterns of northern hazes were not fully evident until the high-phase-angle survey at **PJ12**. The PJ12 composite map is the first detailed map of the northern hemisphere hazes.

Linear bands in the Bland Zone

At every perijove we see long linear bands in the bland zone (BZ): one or more long narrow dark bands, associated with high-level bright band(s) nearer the terminator, which often lie adjacent.
[At **PJ9**, the typical bundle of these bands included an especially striking pair, one bright white (rainbow-coloured near the terminator) and one very dark brown (and methane-dark).]
These bands are usually slightly oblique in latitude, with a p.(E) end at 64-65ºNc (the N edge of the bland zone), and a f.(W) end at ~58-59ºNc (within the N5 domain) but often continuous with bands curving southwards across the N5 domain. But a minority have a segment running due E-W in the BZ. The bands (esp. the dark bands) can be seen around much of the zone under full sun, so their pattern can be traced in composite polar maps, esp. PJ9, as well as the PJ12 high-phase-angle map. They are typically spaced ~27-48 deg apart in longitude (range of spacings in the PJ9 and PJ12 maps; mean = 37.4 deg from 11 bands, thus wavenumber ~ 9.6).

PJ12 global view: [with references to figures in my PJ12 report, copied above in miniature]

This composite near-terminator RGB map (Figure N3) shows the pale bluish-white North Polar Hood (NPH) extending down to the Bland Zone (~64ºN), in which the usual long linear slightly oblique bands can be seen. From these bands, similarly bluish-white bands and arcs extend to the south in huge waves and dramatic swirls. They give a 3D impression, as if the bright bands or areas are elevated cloud decks casting shadows (dark bands) – although some also have a dark band on the sunward edge. Some of the more extended areas at lower latitudes partially colocalise with FFRs, but the more conspicuous haze bands do not appear to be affected by the underlying circulations, as they run unperturbed across FFRs and an AWO (compare with Figure N4, the RGB map under high sun).

The waves and swirls may be divisible into three tiers: one of high contrast from ~63 to 51ºN (i.e. from the N6 to the N5 jet, overlapping both); one of lower contrast down to ~45-39ºN (the N4 and N3 jets); & one of very low contrast and finer texture, down to ~31ºN (the N2 jet).

Figure N5 is a methane-band map of the northern hemisphere. It shows multiple edges to the methane-bright NPH, which correspond very well to the waves and swirls seen in the high-phase-angle colour map.

Other JunoCam maps:

PJ9: Although not nearly as revealing as the PJ12 map, it confirmed some of the main features: at 59-65ºNc, the shallowly oblique linear bands of the BZ; and at ~40-50ºN, steeply oblique and ⊃-shaped bands, largely over the N4 domain but not consistently placed.

PJ11, PJ13, PJ14: The tracing of the haze bands was much more limited in those maps, but was consistent with what we see at PJ12, i.e. extensive complex haze bands near the terminator. *PJ11 Fig.3* showed them over the N3/N4/N5 domains down to 38ºN. At PJ13 and PJ14, with less extensive latitude coverage, they were seen down to 45ºN. [& see above for the same in methane maps]

Discussion [from PJ12]:

South of the N6 jet, these hazes do not obviously trace out the known zonal wind profile, but they may be influenced by it, as their latitudinal limits suggest. This is a consistent pattern at other perijoves, as noted above. The outer edges of the NPH and haze patterns (coinciding in methane and RGB maps), despite their great irregularity, are consistently centred on the N5 and N4 jets. [See Table 1 in the Extended Summary.]

The patterns could largely be reproduced if the white hazes were arising in the N4 and N5 domains, and spreading northwards and southwards until entrained by the next or next-but-one prograde jet. It may be significant that the N4 and N5 domains are largely filled with large FFRs which generate the most frequent lightning strikes on the planet, so these thunderstorms could be generating the high-altitude white hazes. Indeed, the white streaks in FFRs are methane-bright (see Background, above).

Alternatively, the haze may be formed by aerosols created by aurorae, as this is the preferred explanation for the main polar hoods, and the northern auroral oval extends down to ~53ºNc [Vincent et al., 2000, & references therein].

Results (2): Local patterns

Linear bands in the Bland Zone

The characteristic haze bands of the northern domains were revealed at the first perijove, PJ1: notably, two long linear bands in the Bland Zone, and a high-altitude cloud sunlit beyond the terminator at 55-61ºNc (i.e., also in the BZ, though it curves south into the complex bands of the N5 domain). These were reported in [Orton et al., GRL] . [The latitude is 55-61ºNc in Gerald's map but 63ºN in Orton et al. Latitudes in this paper are said to be 'centric but in fact appear to be 'graphic.] (We have never again noted a high-altitude cloud that protrudes so prominently over the terminator, but we cannot make a definite statement about this because the image processing has changed multiple times as the mission proceeded.)

The dark bands are brown when colour data are adequate, and are always methane-dark (whereas the bright bands are only weakly methane-bright). The dark brown bands are not shadows, as they may be on the sunward side of the white bands, and are also seen under high sun. They are more likely to be thinnings in the diffuse bright haze overlying the Bland Zone, although shadowing may enhance them ner the terminator [see Discussion below]. These patterns were described in our reports on PJ3 and PJ4 and have been seen at every perijove since.

There is diurnal variation in the visibility of these bands, as we have also noted in the south polar region. I have done a visual assessment for all PJs from PJ1 to PJ13 using the over-the-north-pole (MEA) images (in order to avoid effects of phase angle or emission angle). [By PJ14, the MEA image was some way from the north pole so not reliable for this purpose.] On the morning side, both dark and bright bands are always present: the dark bands are almost always long (extending around a large fraction of the daylit side), whereas white bands are of varying intensity, sometimes long but sometimes shorter and/or weak (most visible near the dawn terminator). On the afternoon side, bands are less extensive; sometimes hardly present (PJ3, PJ8, PJ12); usually there are both bright and dark bands; sometimes the bright band is particularly bright, at or near the dusk terminator (PJ1, PJ11, PJ13). Thus, dark bands tend to be relatively more conspicuous in the morning, and bright bands in the late afternoon. The same diurnal contrast (dark band at dawn and by day, bright band at dusk) is consistently observed for the long band in the south polar region (esp. PJ5, PJ10, PJ12, PJ14).

The bright bands are sometimes seen as 'rainbow bands', when viewed close up at the dusk terminator (see below). These were recorded at PJ1 [the projecting cloud], PJ4 [when we discussed the phenomenon at length], PJ8, PJ9 and PJ13. PJ8 was the first time that some showed up in two successive images, confirming their reality, as previous images were not taken close enough in time to catch the bands twice under similar lighting conditions. The south polar long band has also been confirmed repeatedly as a rainbow band.

N5-AWOs lie at the south edge of the BZ, and we often see the linear bands overlying them, at or near the dusk terminator (where the hi-res images are obtained). This was noted at PJ4*, PJ8 (white band), PJ9 (brown bands), PJ11*, and PJ13*(over a pair of small AWOs which could be merging). *[In these cases, the overlying band was a rainbow band.] The bands appear undisturbed by the ovals, except for some distortion over the merging ovals at PJ13. We have noticed haze bands running across other northern AWOs (and there was also an example near the south pole at PJ8). These examples suggest that the circulations of these AWOs do not extend to the altitude of the haze bands.

Haze bands further south

From PJ1 to PJ4, the hi-res images taken as Juno swooped down towards perijove often showed conspicuous haze bands ('cloud lanes') near the terminator below 60ºNc -- some continuous with the BZ linear bands, but also separate linear bands lying at various angles, and some more diffuse bands. They are widespread over the N5 and N4 domains, and sometimes are seen all the way down to the NNTB (viz. at PJ1 and PJ3). These evidently belong to the waves and swirls described above under 'Global patterns'.

(After PJ4, as the orbit evolved, the terminator was usually not covered in images taken below 60ºNc, except at PJ9 when the spacecraft was tilted and some excellent images of these haze bands were obtained. However, the north pole MEA images continue to show these haze bands at all perijoves, albeit near the limb.)

Like the BZ linear bands, the bands further south are bright at the terminator indicating their high altitude, some appear as rainbow bands, and some cross AWOs without evident perturbation. Often these haze streaks seem to have 'shadows', which commonly appear brown [Discussion from PJ3 & PJ4 transferred to Discussion section.]. The preceding section already covers bands overlying N5-AWOs. Here are notes from some perijoves [some from my posted reports, and others sent privately to the JunoCam team]:

PJ1: North of the BZ, the PJ1 images showed many oblique bands along the terminator all the way down to the NNTB. [Gerald's latest versions show rainbow bands, including one over NN-WS-4. *High-quality north polar hemispheric maps of these PJ1 images would be worthwhile*.]

PJ3: Streaks of white haze seen at or even beyond the terminator must be at high altitude, which is confirmed for some as they are methane-bright. Note a narrow diffuse band of white haze lying across the NNTB, which seems to cast a short shadow in image 105, and a much longer shadow 12 minutes later in image 107. [*Later PJ3 products:* A merged north polar map shows complex bands near the terminator, in the BZ and further south. Improved image 107 (with NN-LRS-1) shows a rainbow band lying across the NNTB and into the NTZ.]

PJ4: Narrow bands of haze, appearing white near the terminator or across it, are common over all the region. Figure 3 is enhanced to display some of the high-level haze bands near and over the terminator. There is an extensive complex of them across the N3-N4-N5 domains. Most curious are 'rainbow bands' of haze, including one which lies over a N5-AWO.

[From PJ5 on, the northern mid-latitudes were usually not covered near the terminator.]

PJ9: [Rainbow bands and a brown band, crossing a N5-AWO, are discussed above under 'Bland Zone'.] Immediately south of this is a N4-AWO which is likewise crossed by a haze band runnning east-west, but this is a white band.

PJ11: The north polar map shows the usual features very well, including the BZ and complex patterns of bands to the south; most (though not all) of these trace out the zonal wind profiles of the N5 and N4 domains. Fig.4 shows a long linear haze band at 43ºNc on the south flank of the N4 jet.

PJ13: As usual there are linear haze bands in the BZ, often continuous with disparate swirls of haze bands to the south. One of the former is a very bright rainbow band, overlying what may be a pair of small merging N5-AWOs. A brown extension from it (marked by a dashed white line in Fig.2) runs roughly south, sinuously, becoming a brown-and-white haze band that overlies a N4 AWO largely enclosed by an FFR. [This whole curving band is clearly seen in the methane map, done after my report, which shows a good match to the RGB patterns. This is probably one of those great swirls or loops of the edge of the NPH that were visualised at PJ12.

Discussion: Brightness, colours, and altitudes of the bands

(Partly adapted from my report on SPR haze bands [Rogers, 2017 Nov 23]. This was itself a summary of previous comments, esp. in the PJ3 and PJ4 reports.)

White bands are seen mainly near the terminator, sometimes projecting across it, demonstrating their high altitude. Sometimes they are bright bluish on one side and reddish on the other side (*'rainbow bands'*). *Brown bands* can sometimes be seen right across the sunlit part of the region, and can be very dark near the terminator. (In methane images, those in the northern bland zone are notably methane-dark, but those in the south polar region are not.) We have various hypotheses for the multiple colours, some or all of which may be true, but no agreed conclusion yet.

White bands, obviously, are high-altitude bands which are illuminated by sunlight near the terminator. They are sometimes visible in methane images, but the relationship is not simple. In the BZ they are often not conspicuously methane-bright, possibly because they are embedded in the extended NPH collar. Further south they generally align with methane-bright hazes but these may be more extensive [*this should be checked by alignment of hi-res maps*]. (There is a similar mismatch in the south polar region, which may be due to the polar hoods and the white haze bands being made of particles with different sizes and scattering properties.) It seems likely that the white bands are higher than the polar hoods, because we have never noticed the edges of the polar hoods projecting over the terminator. Indeed the polar hoods are not obviously bright in JunoCam RGB images, whereas they do appear bright in blue-light images taken from low latitudes (ground-based or Hubble or Voyager).

Rainbow bands: We had an extensive discussion on the PJ4 images, summarised thus in my report:

> "From discussions with Gerald and with Mike Caplinger of the JunoCam team, it is still not clear if the colour fringing is real or not. Possible artefacts include scattered light in the camera, and residual colour gradients across the image strips (as seen on the dark side; this might explain the blue fringe in some cases), but I am not sure if these can explain all these 'rainbow bands'."

Several of them have now been confirmed in two successive images (at PJ8 and PJ9 [see Figure] – and also one at PJ1; so these are not camera artefacts), and the phenomenon is now familiar so I have no doubt that it is real. The bluish colour is almost always on the sunlit side, and the reddish colour on the shadowed side; the rare exceptions may be due to more complex banding. I suspect the bluish colour is due to wavelength-dependent scattering of light in the thin outer fringe of the band, whereas the reddish colour is due to either of the following explanations for brown bands.

Brown bands : The following possible explanations have been proposed, and some or all could be true:
--Alongside the terminator, they may be shadows cast by the white bands, with diffusely scattered red light (like a stratospheric volcanic sunset on Earth). This is especially likely for those on the NNTB, as the main NPH does not extend to such low latitudes.

--They may be relatively clear lanes within the methane-bright polar hoods (which are diffuse and pale bluish-white, not usually noticed in close-up images), exposing the browner atmosphere below. This is the likely explanation of those seen under high sun, such as the bands in the BZ (see below).
--As brown bands are usually adjacent to white bands, these may be waves of alternating thinner and thicker haze, and/or, waves in which particles are tilted at slightly different angles. (These may be caused by vertical waves in the upper atmosphere, as we sometimes see on Earth.)

We have also sometimes suspected that brown bands could be bands of brown aerosols, as suggested by cases where one is seen lying across an AWO.
However, I now believe that the dark (brown) bands in the Bland Zone (and near the south pole; see below) are clear lanes in a widespread bluish-white haze, for the following reasons:
--They are methane-dark.
--The global high-phase-angle maps at PJ12 do show widespread bluish-white hazes down to ~45ºN (the N4 jet), and much more faintly down to ~31ºN (the N2 jet). These are confirmed by methane maps from this and other perijoves down to ~45ºN, and by UV maps from Hubble down to ~31ºN.
--It would be difficult to account for bands of brown aerosol that remain chemically distinct from adjacent bands of white aerosol over long distances.
& In hi-res images:
--Where fairly long and straight brown bands extend to the terminator (Figures from PJ1 and PJ8), they do not become bright at the terminator, as would be expected for bands of overlying aerosol whatever their colour.
--At PJ9, v-hi-res images showed brown bands crossing a N5-AWO, giving the visual impression that they are bands of a brown aerosol overlying the main cloud deck. However, as the region rotated towards the terminator, the brown bands (esp. the one that crossed the N5-AWO) did not become bright; if anything, they became darker relative to their surroundings [see new version of the figure]. (Brightness adjustment [not saved] indicates that the contrast in the brown band over the AWO is much the same as outside it.)
--At PJ12 in the MEA image, a small bright cyclonic vortex on the N edge of the BZ appeared to have higher contrast within a brown band than features outside it.

The long-lived Long Band in the south polar region is likely to be similar to the linear bands in the BZ [see my report (2017 Nov.23), and other reports up to PJ12]. In the good series of maps at PJ10, the Long Band apparently consisted of fixed alternating dark and bright bands (perhaps waves), the dark bands being more prominent at dawn and by day, and the bright bands at dusk. These properties are consistent with its appearance at other perijoves. We have not determined consistently whether the dark and bright bands are adjacent or coincident, but this is difficult because it depends on accurate alignment of polar projection maps of noisy methane images taken from very different viewpoints at dawn and dusk. It seems likely that the dark and bright bands are adjacent but overlapping, depending on the solar angle. The Long Band is often seen as a rainbow band, and in recent perijoves it has been dark in methane images. (Earlier it was not visible in methane images, which could have been due to subdued and variable expression of its dark phase within the SPH, or the poorer quality of the images.)

Detached haze layers at the limb

Juno's low-altitude perijoves give a good opportunity to search for distinct haze layers on the horizon. The only previous record of such a haze layer is by Rages et al.(1999):
Rages K, Beebe R & Senske D (1999) Icarus 139, 211-226. 'Jovian stratospheric hazes: The high phase angle view from Galileo.'

> In a Galileo orbiter image at E4, a discrete layer detached from the limb was present at 60°Ng (57ºNc), but not in another image at different longitude. Bright streaks running roughly north–south were also present on Jupiter's crescent at 60°Ng. This report is consistent with our obs'ns of dense bands and swirls of haze over the N5 domain.

Gerald has shown that there is a distinct haze layer at the limb in PJ14 images 23 & 24. It is over the orange NNTB, or possibly slightly further north.

He also made limb surveys for previous perijoves but the only feature resembling detached haze was in PJ12 image 87: there was a prominent oblique feature at one edge which was also over the NNTB, and extended into a fainter detached layer which lies over a bright unnamed AWO in the N2 domain.

Such haze layers may have been undetectable in earlier JunoCam images because of the higher altitude, or the viewing angle towards the horizon. It is also conceivable that JunoCam will detect haze layers at higher latitudes as the orbit evolves to move perijove northwards.

FIGURES: See attached Powerpoint file (talk at EPSC, Berlin, 2018)
