A New, Long-lived, Jupiter Mesoscale Wave Observed at Visible Wavelengths

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Received 2018 April 30; revised 2018 May 31; accepted 2018 June 4; published 2018 August 2

Abstract

Small-scale waves were observed along the boundary between Jupiter’s North Equatorial Belt (NEB) and North Tropical Zone, ∼16°5 N planetographic latitude in Hubble Space Telescope data in 2012 and throughout 2015–2018, observable at all wavelengths from the UV to the near-IR. At peak visibility, the waves have sufficient contrast (∼10%) to be observed from ground-based telescopes. They have a typical wavelength of about 1°2 (1400 km), variable-length wave trains, and westward phase speeds of a few m s⁻¹ or less. New analysis of Voyager 2 data shows similar wave trains over at least 300 hr. Some waves appear curved when over cyclones and anticyclones, but most are straight, but tilted, shifting in latitude as they pass vortices. Based on their wavelengths, phase speeds, and faint appearance at high-altitude sensitive passbands, the observed NEB waves are consistent with inertia-gravity waves (IGWs) at 500 mbar pressure level, though formation altitude is not well constrained. Preliminary General Circulation Model simulations generate IGWs from vortices interacting with the environment and can reproduce the observed wavelengths and orientations. Several mechanisms can generate these waves, and all may contribute: geostrophic adjustment of cyclones; cyclone/anticyclone interactions; wind interactions with obstructions or heat pulses from convection; or changing vertical wind shear. However, observations also show that the presence of vortices and/or regions of convection are not sufficient by themselves for wave formation, implying that a change in vertical structure may affect their stability, or that changes in haze properties may affect their visibility.

Key words: planets and satellites: atmospheres – waves

1. Introduction

Small-scale waves, with 100–300 km wavelengths (~0°1–0°2 of longitude), have been observed on Jupiter multiple times, from the ubiquitous inertia-gravity waves (IGWs) seen by Voyager (Flasar & Gierasch 1986; Simon et al. 2015) to the equatorial gravity waves observed by Galileo (Arregi et al. 2009) or the Kelvin waves observed by New Horizons (Simon et al. 2015). However, another wave with a larger wavelength (~1°2, 1400 km), has also been observed in the North Equatorial Belt (NEB), near 16°5 N (planetographic latitude is used throughout, unless otherwise indicated). One such NEB wave was noted in a Voyager 2 image but not noticed again until Hubble Space Telescope (HST) imaging in 2015 (Smith et al. 1979; Conrath et al. 1981; Simon et al. 2015). Simon et al. (2015) postulated that the NEB waves were formed as part of a baroclinic instability during cyclogenesis; however, on many previous dates cyclones were present, or had recently formed, without such waves evident.

Here we re-examine HST multi-color imaging data sets from 2012 to 2018, as well as the full Voyager 2 approach data. In addition, we report on NEB wave appearances in multiple visible and infrared ground-based data sets. In the past few years, the NEB waves have been observed sporadically, with lifetimes of at least tens of hours, and are sometimes prominent enough to be seen in images acquired with ground-based telescopes. Section 2 summarizes these observational data. Section 3 describes the measurable aspects of the NEB waves. Preliminary General Circulation Modeling (GCM) is discussed in Section 4, with discussion of wave types and Earth analogies in Section 5.

2. Observations

Smith et al. (1979) showed a faint wave in Voyager 2 Imaging Subsystem Narrow-Angle Camera (NAC) data, reported in a single violet image on 1979 July 3 (see their Figure 3) in the NEB. Subsequent searches show the waves to be present almost every time this longitude region (~60°W System III) of the NEB was observed with sufficient spatial resolution, as shown in Figure 1. The waves are short, repeating, linear features visible against the background clouds. In the highest spatial resolution NAC images (~30 km pixel⁻¹), this NEB wave is much harder to spot, perhaps due to its low contrast. Near the closest approach to Jupiter (1979 July 9), the Wide-Angle Camera (WAC) also offered a view of the NEB waves, with spatial resolution of ~115 km pixel⁻¹. Wave crests were identified in at least 107
Voyager 2 images from 1979 June 26 to July 8, and at all wavelengths observed, with highest contrast in the violet images (see Appendix Table 5).

A similar NEB wave was first noted, post-Voyager, in HST images in 2015, in part because of its extensive train of wave crests, and high contrast (Simon et al. 2015). In HST images 13 months later, no long wave trains were seen, and a small wave packet (∼5° length) was only observed over one cyclone. However, in 2017, NEB waves could be spotted again over extensive sections of longitude (Figure 2). These waves were also observed at 5 μm for the first time, both from ground-based facilities and NASA’s Juno spacecraft, as reported in companion papers (Adriani et al. 2018; Fletcher et al. 2018). A further search in older HST data sets revealed a faint NEB wave in 2012 images, as well (Appendix Figure 10). The appearance and longevity for both Voyager 2 and HST observations are noted in Table 1; dates without any observed NEB waves are shaded gray. Single hemisphere views (∼80° to 260°W) in 2017 March also did not reveal any similar NEB waves.

In 2017, NEB waves were also observable in ground-based observations, even using modest-size telescopes (0.36–0.5 m diameter). They were very prominent and well contrasted in observations obtained at the 1.05 m telescope at the Pic du Midi Observatory (Figure 3). Table 2 lists the many times that wave features were observed. In some cases, a wave train was observed with enough continuity to be identified as the same feature, even if individual wave crests cannot be uniquely matched. Several wave trains were observed for more than 1 month. Appendix Figures 11–13 show a selection of these ground-based images. NEB waves were observed again in 2018 with lower cloud contrast than in 2017 and also in locations close to the system of cyclones and anticyclones.

Figure 1. Voyager 2 time-sequence of NEB waves from the Imaging Subsystem NAC. Each map was produced at the same spatial resolution (0.1/px) and centered near 16°N latitude, mapped over 20° in planetographic latitude and 60° in longitude (at closer range only part of that area is visible). A light unsharp mask was applied to increase feature visibility. The June 26 map was obtained in the green filter, the rest in the violet filter. The wave train is difficult to spot on June 30, but evident on surrounding dates (lines added on July 3 to guide the eye).
3. Analysis

In Voyager 2 and HST images, the NEB waves have the most contrast at violet wavelengths, often with lower contrast at red wavelengths. When well-formed and observed at all the available wavelengths in HST data, the contrast is lowest at UV and methane absorption-band wavelengths, Figure 4. In 2012 September and 2018 February, wave crests are seen only at UV wavelengths (275 nm), but not in visible to near-IR continuum or methane gas absorption bands. At a wavelength of 275 nm, Rayleigh scattering limits visibility (optical depth 1) to altitudes above 0.5 bar and absorption in the methane band at 890 nm produces optical depth 1 at \( \sim 0.1-0.2 \) bar. The waves have maximum contrast, \( \sim 10\% \), in violet-blue wavelengths and are separate from the background cloud tops (\( \sim 1 \) bar), which have maximum contrast in the red and near-IR continuum. The NEB wave visibility is likely due to a combination of their altitude location at 0.1–0.5 bar, just above the cloud tops of the vortices, and aerosol/haze properties at short wavelengths. If the waves were located in the main clouds near 1 bar, the red and continuum bands would show maximum contrast, while waves in the stratospheric hazes would have maximum contrast in the UV.

The measurements of latitudinal extent depend on the wave contrast, but also that of the background cloud features; it is not always obvious where the wave crest begins or ends. Table 3 shows the average latitudinal extent of the waves, \( \sim 2^\circ.5 \). The waves are largely aligned north–south, with slight westward tilts with latitude. The most extreme tilts are about 33\(^\circ\) and may show curvature, usually near cyclones. For example, the wave over the cyclone in 2016 February, and over a cyclone near the east end of the wave train in 2015 January, Figure 10. This can also be seen in the Pic-du Midi imaging data in Figure 3.

The central latitude of the NEB waves also varies slightly as seen in Tables 1 and 2, but much of this is likely due to the nearby vortices, which may dynamically shift the wave systems or at least mask their visibility. For example, in 2012 the average planetographic latitude was 17°7′ ± 0°4′ at longitudes away from any anticyclone, while for wave crests near the anticyclones it was 16°7′ ± 0°3′, implying the anticyclones “shift” the NEB waves southward. In contrast, the cyclones push the wave crests, or their visibility, northward; wave crests over cyclones in 1979 July average 17°1′ ± 0°3′, and in 2016 February average 16°9′ ± 0°6′, while in 2017 April, they average 16°3′ ± 0°4′ away from any cyclones. Thus, the presence of cyclones or anticyclones accounts for much of...
### Table 1: Summary of Spacecraft Observations

| Mission | Date                  | Sys III. Longitude (°) | Filters (nm) | Related Features | Visibility Notes |
|---------|-----------------------|------------------------|--------------|------------------|------------------|
| Voyager 1 | 1979 Jan 08 to 1979 Mar 05 | ... | ... | A, C, S | ... |
| Voyager 2 | 1979 Jun 26 to 1979 Jul 08 | 30–90 | 325, 400, 585, 615, 619 | FC. Some S to East, A & C elsewhere | ... |
| HST     | 1995 Feb 17, 1995 Oct 05, 1996 Oct 21, 2007 Feb 26, 2007 Mar 26, 2008 May 10 | ... | ... | A, C, S | ... |
| HST     | 2012 Sep 20 | 295–300, 20–45, 130–160, 200–260 | 275 | A, C, FC?, S Faint, ≥20 hr None at 763 nm |
| HST     | 2015 Jan 19 | 180–360 | 275, 343, 395, 502, 547, 631, 658, 889 | A, C, FC, S | ≥20 hr |
| HST     | 2016 Feb 09 | 50–55 | 343, 395, 467, 502, 547, 631, 658 | C. Elsewhere A, S. | ≥10 hr None at 275, 889 |
| HST     | 2016 Dec 11 | 70–100 | 343, 395, 502, 631, 727, 750 | C. Elsewhere A, S Faint, ~10 hr None in 225, 275, 889 |
| HST     | 2017 Jan 11 | 85–135, 225–260 | 225, 275, 343, 395, 502, 631, 727, 750, 889 | C. Nearby Faint at 225 and 889 |
| HST     | 2017 Feb 01 | 25–75, 160–210 | 225, 275, 343, 395, 502, 631, 727, 750, 889 | C. Nearby A, S elsewhere | ≥10 hr |
| HST     | 2017 Apr 03 | 5–55, 235–305 | 275, 343, 395, 502, 547, 631, 658, 889 | A, C, FC. Some S to East | ≥10 to 20 hr, but fading |
| HST*    | 2017 May 19 | 135–150, 190–215 | 343, 395, 502, 631, 727 | S, A and FC at ends Faint in 135–150 portion. None in 275, 889, faint in 727 |
| HST*    | 2017 Jul 11 | 315–20 | 275, 343, 395, 502, 631, 727, 750 | A, C, FC. Weak S nearby? Faint in 275. None at 889 |
| HST*    | 2018 Feb 06 | 175–230 | 275 | S, FC?, nearby A Faint in 275. None in 225, 343, 395, 502, 631, 727, 750, 889 |
| HST     | 2018 Apr 01 | 180–230, 285–300 | 343, 395, 502 | C, A Faint in 275, 631. None in 225, 889 |
| HST     | 2018 Apr 17 | 35–180, 200–270 | 275, 343, 395, 502, 467, 631, 658, 889 | C, A, S Faint at 225 and 889 |

**Notes.**

a Filter wavelengths given here correspond to the names of WFC3/UVIS filters, as given in Table 6.2 of Dressel (2017).

b Related features are those that are prominent over longitudes covered by the waves, or, on dates without waves, present at any longitude. A: Anticyclones, C: cyclones, FC: forming cyclones (less-defined shape), S: NEB storms.

c All observations included global coverage, except 2017 May and June and 2018 February.
Figure 3. Ground-based observations of the NEB at visible wavelengths (top and bottom right) and in the methane absorption band (bottom left). In this image set, the NEB waves occur primarily in locations where high hazes are located; in the methane band, an apparent chain of vortices forms a larger-scale wave with a dearth of haze opacity to the west of the smaller NEB waves (Fletcher et al. 2017, 2018) Note: 15° centric = ~17° graphic latitude.

Table 2

| Observer | Date* | Sys III. Longitude (°) | Graphic Latitude (°) | Filter | Related Features‡ | λ(°) |
|----------|-------|------------------------|----------------------|--------|-------------------|------|
| P. Miles | 2017 Feb 22 | 209–234 | 15.9 ± 1.1 | IR700nm | ... | ... |
| D. Peach | 2017 Mar 05 | 100–116 | 17.8 ± 1.1 | Visible | A | 1.7 ± 0.3 |
| D. Peach | 2017 Mar 07(b) | 71–153 | 18.2 ± 1.1 | IR700nm | ... | 1.5 ± 0.3 |
| A. Garbellini | 2017 Mar 12(b) | 2–12 | 18.0 ± 1.1 | Visible | C, S | 1.9 ± 0.4 |
| C. Go | 2017 Mar 24(b) | 7–57 | 16.8 ± 1.2 | Visible | A, S | 1.6 ± 0.3 |
| T. Olivetti | 2017 Mar 31(c) | 23–57 | 17.2 ± 1.1 | Visible | A, S | 1.7 ± 0.4 |
| R. Bossman | 2017 Apr 08 | 60–67 | 15.7 ± 1.0 | Visible | A | 1.6 ± 0.4 |
| C. Go | 2017 Apr 10(c) | 25–30 | 16.0 ± 0.5 | Visible | A, C, S | 1.5 ± 0.4 |
| M. Kardasis | 2017 Apr 15(d) | 312–350 | 17.1 ± 0.9 | Visible | A, S | 1.4 ± 0.3 |
| C. Go | 2017 Apr 17(d) | 318–351 | 16.7 ± 0.9 | Visible | A, C, S | 1.4 ± 0.5 |
| C. Go | 2017 Apr 19(d) | 282–322 | 17.7 ± 0.4 | Visible | A, C, S | 1.4 ± 0.3 |
| T. Olivetti | 2017 Apr 21(d) | 303–338 | 17.5 ± 0.6 | Visible | A, S | 1.6 ± 0.4 |
| C. Go | 2017 Apr 24(d) | 302–325 | 17.5 ± 0.6 | Visible | C, S | 1.3 ± 0.4 |
| C. Go | 2017 Apr 26(e) | 212–259 | 17.7 ± 0.7 | Visible | A, C, S | 2.2 ± 0.5 |
| A. Wesley | 2017 Apr 29(d) | 281–294 | 17.9 ± 0.4 | Visible | A, S | 2.1 ± 0.4 |
| C. Go | 2017 May 01 | 244–275 | 17.3 ± 0.4 | Visible | A | 1.5 ± 0.5 |
| A. Wesley | 2017 May 03(e) | 205–212 | 18.8 ± 1.1 | IR685nm | ... | ... |
| A. Wesley | 2017 May 05(f) | 89–118 | 17.0 ± 1.7 | Visible | C, S | 2.0 ± 0.4 |
| C. Go | 2017 May 10(e) | 199–213 | 17.0 ± 0.6 | Visible | A, S | 2.1 ± 0.4 |
| C. Go | 2017 May 18(e) | 227–263 | 16.8 ± 0.4 | Visible | A, S | 1.9 ± 0.5 |
| Pic-Net | 2017 Jun 10(f) | 62–285 | 17.3 ± 0.9 | Visible | A | 1.2 ± 0.1 |
| C. Zanelli | 2017 Jun 13(f) | 90–113 | 17.0 ± 0.6 | Visible | A, S | ... |

Notes.
* Letters (b) to (f) indicate systems that are identified in different dates.
‡ Related features are as in Table 1. Appendix Figure 11 shows maps of the NEB on these images displaying the wave activity. The longitudinal range contains the extremes of the different wave systems that can be seen on different dates. In some cases, the images show fragmented waves that do not necessarily extend all the way between both limits.

The variation in central wave crest latitude in Table 1. Shifts of this nature are evident in Figure 2, near the central anticyclone, and in Figure 10 on the west end of the 2017 May wave train. The possible dynamic shift may be due to movement in the zonal flow (Johnson et al. 2018) or to a local change in the condensable haze/cloud that traces the waves near the vortices. Alternatively, it may be an observational effect caused by higher cloud tops in the anticyclones or cloud depletion above the cyclones at the vertical level of the waves, rendering them unobservable in the cloud fields.

The length of the wave trains is highly variable, from 5° in 2016 February (over a single cyclone), to covering most of a full hemisphere in 2015. However, the longitudinal wavelength has been nearly constant from the Voyager era to HST (Table 3) and in good agreement with ground-based data (Table 2). In the Voyager 2 data, an NEB wave is seen over at least 12 days,
The contrast of the wave crests above the background features is

...Minimum topography, by convective storms, by hurricanes, jets and
all observed cases in Table 1, cyclones and anticyclones are
as well as convective heat pulses may also produce waves. In

...because there were many images acquired over 6 days, some
image set, Voyager 2 (Plougonven & Zhang 2014; Nolan &

...White anticyclonic regions are seen near 162°W and 188°W in the image at
395 nm. Wave crests appear as periodic brightness variations above the
background clouds; the 395 nm curve is shifted by 0.1 for clarity. Maximum

...275, 395, and 658 nm, respectively. On Earth, gravity waves are generated by

...and anticyclones; Plougonven & Zhang 2014; Nolan &

...HST observations occur over 6 days, such that the images are acquired with 0.1 mbar to 7 bars and was initialized with a temperature

...The model is initially in geostrophic balance, and perturbations may be added to simulate the presence of spots in this region. The

...Case 1: Merging anticyclones, with cyclones also present in the domain. The spots are initialized with a size of 3° diameter and an initial rotational amplitude of 40 m s⁻¹. After approximately 14 simulated days, two of the anticyclones merge, producing wave trains similar to the wave trains in the observations (Figure 6 top panel and Figure 7 left panel).

...Case 2: Merging anticyclones, with no cyclones present. The spots are initialized with the same properties as in Case 1. After approximately 35 simulated days, the anticyclones merge, producing wave trains (Figure 6 middle panel and Figure 7 middle panel).

...Case 3: Merging cyclones. The spots size and amplitude are initialized as in the previous cases. After approximately 20 simulated days, the two cyclones merge, producing wave trains similar to those observed (Figure 6 bottom panel and Figure 7 right panel).

...The waves produced in the simulations show morphological similarities to the observed NEB waves. Those forming off the cyclones show curvature, similar to those in Figure 8, top and bottom panels. In the model, the passage of an anticyclone to the north of the cyclones appears to make the wave trains more stable, reducing the tilt of the crests, and shifting the wave trains north and south, similar to Figure 8, all three panels.

...The simulations produce potential vorticity patterns that resemble the observed waves in terms of wavelength, speed, and lifetime (Table 4), but the HST imaging data directly observe aerosol opacity rather than potential vorticity. Models show that cloud opacity maps can differ significantly from potential vorticity maps (Marcus 2004; Palotai et al. 2014). Although our simulations imply that the waves may be commonly produced by vortex interactions, details of cloud microphysics may play a role in determining whether the waves are visible in imaging data.

Figure 4. Brightness scans at 16°3 ± 0°1 in HST images from 2018 April 17. White anticyclonic regions are seen near 162°W and 188°W in the image at 395 nm. Wave crests appear as periodic brightness variations above the background features; the 395 nm curve is shifted by 0.1 for clarity. Maximum contrast of the wave crests above the background features is ~3%, ~10%, and ~6% at 275, 395, and 658 nm, respectively.

4. Modeling

On Earth, gravity waves are generated by flow over topography, by convective storms, by hurricanes, jets and fronts systems, and atmospheric dipoles (i.e., pairs of cyclones and anticyclones; Plougonven & Zhang 2014; Nolan & Zhang 2017). On Jupiter, vortex interactions and adjustments, as well as convective heat pulses may also produce waves. In all observed cases in Table 1, cyclones and anticyclones are present, as well as convective regions. We used the Explicit Planetary Isentropic Coordinate (EPIC) GCM (Dowling et al. 1998) to explore some of these scenarios, focusing on the interactions between spots in these regions as a source of gravity waves.

We initialized a small domain model covering 60° in longitude (with 0°23/pixel resolution) and 25° in latitude, from 5° to 30° (with 0°25/pixel resolution). We used the zonal winds derived from Cassini observations (Porco et al. 2003), which, for this region, is indistinguishable within the measurement errors from HST and amateur observations throughout 2017 (Hueso et al. 2017; Tollefson et al. 2017; Johnson et al. 2018). The model has 18 vertical layers extending from 0.01 mbar to 7 bars and was initialized with a temperature profile and Brunt–Väisälä frequency, N, derived from Gemini/TEXES Observations acquired in 2017, Figure 5. For higher pressures, the temperature profile is extrapolated so that the value of the potential temperature decreases linearly with depth. The details of the calculation of the potential temperature in the model are explained in the appendix of Dowling et al. (1998), while the details of the calculation of N can be found in the appendix of Dowling et al. (2006).

The model is initially in geostrophic balance, and perturbations are added to simulate the presence of spots in this region. The EPIC model is initialized in geostrophic balance. Therefore, any perturbation added to an initially equilibrated state will spontaneously radiate gravity waves. These initial, transient, waves radiate concentrically away from the perturbation (i.e., they are neither parallel nor perpendicular to lines of constant latitude). Spot interactions such as mergers are also a source of gravity waves in the model and may better match the observed NEB waves. We explored three types of interactions, with properties of the resulting waves summarized in Table 4:

1. Case 1: Merging anticyclones, with cyclones also present in the domain. The spots are initialized with a size of 3° diameter and an initial rotational amplitude of 40 m s⁻¹. After approximately 14 simulated days, two of the anticyclones merge, producing wave trains similar to the wave trains in the observations (Figure 6 top panel and Figure 7 left panel).

2. Case 2: Merging anticyclones, with no cyclones present. The spots are initialized with the same properties as in Case 1. After approximately 35 simulated days, the anticyclones merge, producing wave trains similar to those observed (Figure 6 middle panel and Figure 7 middle panel).

3. Case 3: Merging cyclones. The spots size and amplitude are initialized as in the previous cases. After approximately 20 simulated days, the two cyclones merge, producing wave trains similar to those observed (Figure 6 bottom panel and Figure 7 right panel).
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5. Discussion

5.1. Wave Formation Mechanisms

Most of the observed NEB wave trains begin on the westward side of cyclones or anticyclones, though not exclusively; all observed NEB wave trains have some sort of vortex present, although sometimes the wave trains extend far from the vortices. Based on the spacecraft observations, they are tightly confined to latitudes of $16.5 \pm 0.5$ and have regularly spaced crests ranging in number from 6 to 12 or more, depending on where one defines the boundaries of an individual wave train. Numerical studies of Earth’s atmosphere have shown that IGWs should be generated in GCMs from the interaction of cyclones and anticyclones (Wang et al. 2009); IGWs are buoyancy waves and include the effects of the Coriolis forces, while pure gravity waves (GW) do not. Small-scale IGWs are common in fluid flows and on Earth, caused by velocity shears, topography, thunderstorms, and geostrophic adjustment (e.g., Fritts 2015). Williams et al. (2003) used modeling and laboratory studies to show that spontaneous adjustment radiation can also form small-scale waves that interact with the baroclinic flow to selectively produce longer wave modes.

Cyclones on Earth are also known to form several other types of atmospheric GWs that could be analogous to the ones seen in this study. First, spiral density or buoyancy waves are observed to be radiating from the center of powerful hurricanes (Nolan & Zhang 2017). These very small horizontal waves have only been observed in the clouds of the hurricanes themselves, not outside of the storm like the Jupiter waves at $17^\circ$N. Earth cyclones can also produce small-scale GWs that radiate away from the storms as they experience baroclinic instabilities (Vallis 2006; Yue et al. 2014). The terrestrial waves also have very small horizontal wavelengths and are only observed in close proximity to the storm in fully, or partially, concentric rings that spread with distance. Lastly, large-scale GWs can be produced from terrestrial cyclones as they go through periods of geostrophic adjustment caused by the “obstruction effect” of local topography. On Earth, these large-scale GWs have large horizontal wavelengths ($\sim$500 km), are observed at greater distances away from the storms (see Figure 3 of Yue et al. 2014), and propagate upwards into the stratosphere. These wave trains are not the same scale or length as Jupiter’s waves, in part because the tropical cyclones are subject to topography, latitudinal drift, and atmospheric conditions that are quite different from conditions in Jupiter’s NEB. Nonetheless, terrestrial tropical cyclones show a potential wave formation mechanism and if conditions allow (such as wave trapping), the wave train can grow.

For Jupiter, the smallest-scale spiral and baroclinic GWs would be below the $\sim$175 km spatial resolution limit of HST. Very fine-scale waves are observed in the NEB (and other regions) in recent JunoCam data with wavelengths of 55–174 km (e.g., Sánchez-Lavega et al. 2018). The highest spatial resolution Voyager 2 data did not include any images of the cyclones near the NEB waves. However, Voyager 1 did observe a large well-formed cyclone at a resolution of $\sim$14 km pixel$^{-1}$ (Figure 9) with a fine-scale structure suggestive of a spiral wave or GW, as well as a few near-horizontal dark streaks with spacings of 250–425 km and lengths of 500–750 km; similar streaks are seen on many Voyager vortices. These features could be part of the formation cycle of the NEB waves seen during Voyager 2 a few months later, but we cannot rule out that they may be unrelated.

However, none of these proposed formation mechanisms currently explain why NEB waves are only observed near some longitudes and are temporally variable. Without constant high-resolution monitoring, it would be next to impossible to connect observed individual wave crests to a specific cyclone or anticyclone, cyclone/anticyclone interaction, or some other sporadic process, even with the combination of spacecraft and ground-based coverage in 2016–2018. It is possible that ALL

Figure 5. Derived Jupiter temperature profile (left) and Brunt–Väisälä, $N$, profile (right) used in the EPIC GCM simulations.
of these processes are producing individual NEB waves on different dates and longitudes, with the wavelength and location governed by atmospheric properties. If such properties change over time, waves may not be able to form, or may not be observable if present.

5.2. Wave Property Analysis

Initial studies had concluded that the NEB waves might be a baroclinic instability (Conrath et al. 1981; Simon et al. 2015). However, this interpretation is problematic for several reasons. First, such an instability would grow with longitude, and there is no evidence of changing wavelength over the longer wave trains. Second, Conrath et al. (1981) showed that the observed wavelength corresponds to a Rossby deformation radius of $\sim 400 \text{ km}$, and this particular wave mode should be confined to the upper troposphere. However, that deformation radius leads to a Brunt–Väisälä frequency, $N$, of $\sim 1.8 \times 10^{-3} \text{ s}^{-1}$, which only occurs below the cloud deck (Figure 5, right). In the fastest growing mode, the vertical scale of the waves would be very small, a few meters at most, too small to produce the observed contrast. Thus, it is hard to reconcile the waves with their observed properties above the cloud deck. Similar analysis of a Rossby wave, which could match the small phase speeds, also produces waves with very small vertical extent, a few meters or less.

As the simulations in Section 4 show that it is easy to generate IGWs/GWs, we now compare the observed NEB wave properties with the properties of an IGW or GW. For an IGW or GW in the Boussinesq approximation for a rotating planet, density variations are neglected except in the buoyancy term, and phase speed has components in both the horizontal or vertical direction, though the vertical component is often small (Dunkerton 2015).

The full IGW dispersion relation, which includes Coriolis forces, is given by (Fritts 2015):

$$\omega - uk = \frac{N^2 k^2 + f^2 m^2 + f^2 / (4H^2)}{k^2 + m^2 + 1 / (4H^2)}$$

Figure 6. Potential vorticity maps for cases #1 (top), #2 (middle), and #3 (bottom) at days 17, 39, and 23 simulated days, respectively. Green indicates cyclonic vorticity, while red is anticyclonic. The produced wave trains are marked.
where \( k \) is the horizontal wavenumber (\( 2\pi/1400 \) km), \( m \) is the vertical wavenumber, \( N \) is the Brunt–Väisälä frequency, \( H \) is the atmospheric scale height, \( f \) is the Coriolis parameter, and \( \omega \) is the wave frequency. For pure GWs, the Coriolis terms disappear, and if vertical wavelength \( \ll 4\pi H \) (\( \sim 315 \) km for \( H = 25 \) km), the \( 1/(4H^2) \) terms can be neglected (Holton & Alexander 2000; Dunkerton 2015; Lane 2015).

At 16°5 latitude, \( f \) is \( \sim 1 \times 10^{-4} \) s\(^{-1}\). As the NEB waves are observed near 500 mbar, we use a value of \( N = 1.1 \times 10^{-2} \) s\(^{-1}\) (Figure 5) and the observed horizontal velocity and wavelength to simultaneously solve for vertical wavenumber, \( m \), and the vertical trace velocities, \( w_T \):

\[
\begin{align*}
    u_T &= u + \frac{1}{k} \left( \frac{N^2k^2 + f^2m^2}{k^2 + m^2} \right), \\
    w_T &= \frac{1}{m} \left( \frac{N^2k^2 + f^2m^2}{k^2 + m^2} \right).
\end{align*}
\]

Assuming the \( u_T = \mathbf{c} = -3.7 \) m s\(^{-1}\) (Table 3 average), the IGW has \( m^2 < 0 \) and does not propagate vertically, while a pure GW has a vertical wavelength of \( \sim 300 \) m. If the full phase speed uncertainty is considered, vertically propagating 400 m or 700 m IGWs are also possible solutions. These yield vertical velocities of a few m s\(^{-1}\), for the propagation GWs and IGWs. This would imply that the waves should be quite visible at the higher altitudes, which is not observed in the UV or methane-banded filtered images (225, 275, and 889 nm). Thus, the non-propagating IGWs would be the preferred solution.

Alternately, the NEB waves may form deeper and vertically propagate above the cloud deck, possibly breaking at a critical level, or becoming ducted above the clouds. If they form below the clouds, near the water layer at 2–4 bars, they must vertically propagate a few scale heights to be visible near 500 mbar. At this depth, the phase speed is not known, but if we assume the same full range of phase speeds above and \( N = 1.8 \times 10^{-3} \) s\(^{-1}\) (Conrath et al. 1981; Simon et al. 2015), this yields solutions for a GW with 1.9–4.5 km vertical wavelength and \( \sim 5–30 \) cm s\(^{-1}\) vertical velocity, or an IGW with wavelength of 2.5 km and 17 cm s\(^{-1}\) vertical velocity. These waves would reach the 500 mbar altitude in about 100 hr. Thus, either GWs or IGWs at this depth are also a plausible solution. It is not clear from the observational constraints if the NEB waves form near 500 mbar, or if they form much deeper and propagate vertically to this pressure. Indeed, 5 micron imaging of these waves, and similar analyses from Cassini CIRS temperature inversions also cannot uniquely constrain the wave formation altitude (Fletcher et al. 2016, 2018).

Lastly, for waves to form, the atmosphere must have the proper static stability. One measure of this is the Richardson number, \( Ri \), defined by

\[
Ri = \frac{N^2}{(\partial u/\partial z)^2},
\]

where \( \partial u/\partial z \) is the vertical wind shear. For \( N^2 = 0 \) (and \( Ri = 0 \)), the atmosphere has neutral stability and no oscillations result. If \( N^2 > 0 \), stable oscillations can result with higher values inhibiting vertical displacement, and if \( N^2 < 0 \) this increases the vertical displacements. In the resulting \( Ri \), at \( Ri < 0.25 \) wind shear dominates and Kelvin–Helmholtz instability (turbulence) may arise, while for \( Ri > 0.25 \) stability generally dominates, with \( N^2 \) determining the oscillation amplitude, damping at higher values (\( N^2 > 1 \)) (Young 2015).

The vertical wind structure in this region of Jupiter’s atmosphere cannot be directly observed, but it can be inferred from the thermal wind equation (Gierasch et al. 1986; Li et al. 2006; Simon-Miller et al. 2006). However, retrievals of the vertical temperature profile from IR data are relatively insensitive to the temperatures below the nominal cloud deck.
Above the cloud deck, $\text{Ri}$ grows to $\gg 1$, which would indicate waves are damped and should not be forming, though it is possible that the active NEB convection is affecting the local stability.

5.3. Wave Temporal Appearance

Any waves that do form may be damped over time or break in the presence of vertical wind shear and critical layer absorption, depositing their energy and disappearing (Lane 2015). If conditions are no longer conducive, no new waves appear. The temporal variability of the NEB waves implies either the static stability is temporally variable, or else ever-present waves are simply not visible due to cloud/haze changes. While we do not know the exact time between the end of the Voyager 1 data and when the 1400 km NEB waves first appear, their presence in the earlier Voyager 2 data indicates that onset of wave formation is $< 100$ days.

Table 3

| Date                  | Latitude (Graphic) | Latitude Extent (°) | $\lambda$ (°) | Velocity, $c$ (m s$^{-1}$) | Phase Speed, $c-u$ (m s$^{-1}$) |
|-----------------------|--------------------|--------------------|--------------|---------------------------|---------------------------------|
| 1979 Jun 26 to 1979 Jul 03 | 17.1 ± 0.3         | 2.2 ± 0.2          | 1.2 ± 0.2    | −24.7 ± 5                 | −5.2 ± 8                        |
| 2012 Sep 20           | 17.2 ± 0.8         | 2.5 ± 0.2          | 1.2 ± 0.3    | inconclusive              |                                 |
| 2015 Jun 19           | 16.1 ± 0.6         | 2.4 ± 0.6          | 1.1 ± 0.1    | inconclusive              |                                 |
| 2016 Feb 09           | 16.9 ± 0.4         | 2.4 ± 0.2          | 1.1 ± 0.1    | −17.5 ± 10                | −2.5 ± 10                       |
| 2016 Dec 11           | 16.1 ± 0.1         | 2.3 ± 0.3          | 1.1 ± 0.1    | inconclusive              |                                 |
| 2017 Jan 11           | 16.5 ± 0.3         | 2.6 ± 0.5          | 1.2 ± 0.1    | −14.2 ± 10                | −4.2 ± 10                       |
| 2017 Feb 01           | 16.5 ± 0.3         | 2.4 ± 0.3          | 1.1 ± 0.1    | Inconclusive              |                                 |
| 2017 Apr 03           | 16.3 ± 0.2         | 2.9 ± 0.5          | 1.2 ± 0.2    | −15 ± 15                  | −3 ± 15                         |
| 2017 May 19           | 16.5 ± 0.5         | 2.4 ± 0.3          | 1.1 ± 0.1    | ...                      | ...                             |
| 2017 Jul 11           | 16.2 ± 0.2         | 2.8 ± 0.4          | 1.1 ± 0.1    | ...                      | ...                             |
| 2018 Feb 06           | 16.2 ± 0.2         | 2.8 ± 0.3          | 1.3 ± 0.2    | ...                      | ...                             |
| 2018 Apr 01           | 16.5 ± 0.7         | 4.3 ± 1.2          | 1.2 ± 0.2    | ...                      | ...                             |
| 2018 Apr 16           | 16.0 ± 0.3         | 2.5 ± 0.5          | 1.1 ± 0.1    | Inconclusive              |                                 |

Note. Negative phase speeds indicate westward motion. For consistency, wave phase speeds are computed with respect to the zonal wind profiles previously measured for those dates (Simon-Miller & Gierasch 2010 for 1979, Tollefson et al. 2017 for 2016, Johnson et al. 2018 for 2017).

Figure 8. HST maps from 2018 April, 2017 April, and 2016 February spanning 80° of longitude and 20° of latitude. These three dates roughly match the three cases shown in Figures 6 and 7. Note that extensive wave trains are seen in 2018 April among cyclones (C) and anticyclones (A). The 2017 April map segment mainly shows anticyclones and features suggestive of a vortex (denoted by ?). In 2016 February, only a small wave train is seen over a single cyclone.
It is of note that the 2015 NEB waves appeared in the same seasonal cycle as those seen during Voyager (northern autumnal equinox) and that identical waves have not been observed at similar southern latitudes. First, the structure of the zonal winds at equivalent north and south latitudes is very different and includes the presence of the Great Red Spot. Additionally, the combination of Jupiter’s orbital eccentricity \( (e = 0.0489) \) and rotational axis obliquity \( (3^\circ.13) \) gives rise to more heating in the north and there has been a marginal detection of a seasonal component to haze thickness or brightness in the UV (Simon-Miller & Gierasch 2010); thicker haze may allow the waves to become more prominent. Unfortunately, there were no high spatial resolution imaging data near intervening northern equinoxes (1991, 2003) to confirm this hypothesis.

Alternately, numerical modeling of the wave-driven Quasi-Quadrennial Oscillation (QQO) showed that forcing a strong equatorial jet to descend in time produces smaller, weaker jets near \( \pm 15^\circ \) latitude in response (Cosentino et al. 2017). These jets vary in altitude and amplitude and could change the vertical wind shear in the region above the NEB cyclones. An alignment of the QQO cycle to the seasons may have a greater cumulative effect on the vertical temperature structure and/or haze thickness in the NEB. However, in the current epoch, the NEB waves have persisted longer than the QQO cycle, and we do not know how long they persisted after Voyager 2. Further observations of thermal and vertical wind structure, as well as near-UV brightness, are clearly needed for periods with and without NEB waves to further elucidate any differences that may be present. Future detailed GCM simulations will include a larger domain space with more realistic boundaries, damping, and exploration of parameter space (temperature profile, wind profile, Brunt–Vaisala frequency) to understand under which conditions they form and best match the observations, including wave train length, motions, and wave crest tilts. We will also explore the effect of different types of perturbations such as heat pulses and planetary-scale waves in producing NEB waves.

## 6. Conclusions

The large visible wavelength data set presented here gives several new insights on a new class of mesoscale waves observed at \( \sim 16^\circ.5 \pm 0^\circ.5 \) latitude. Their wavelength is a nearly constant \( 1^\circ.2 \), and they are observed near both cyclones and anticyclones, sometimes shifting in latitude as they pass a vortex. The observed lifetimes of individual wave trains vary, but can exceed 30 days, and, when at maximum contrast, they are observable in even modest ground-based telescopes. The observed NEB wave properties are more consistent with IGWs than Rossby waves or baroclinic instability, though the latter two cannot be entirely dismissed. Although the NEB waves appear at or above the cloud deck, the altitude of formation is not well constrained.
The presence of the NEB waves in current observations of Jupiter remains perplexing for several reasons. This region is consistently observed to have frequent convective outbreaks, accompanied by several interacting and sometimes merging cyclones, all of which are sources of atmospheric waves. As such, there is no shortage of processes to generate the NEB waves, but why are they so prevalent now and not over the previous 20 years? What has changed in this region for the waves to be present in Voyager-era images, disappear, and then now re-appear? Is their presence predicated on the numbers of cyclones, an indication of some other slowly varying atmospheric condition like vertical wind shear, or on variations in tropospheric haze opacity? Modeling can reproduce IGW/GWs from vortex interactions, but further exploration of parameter space, including the effects of heat pulses to mimic convective outbreaks, is need to determine why they do not form at other times or latitudes. More intensive numerical modeling could also help determine which of these is more likely to reproduce the observed NEB wave train lengths. Further visible and infrared observations of the NEB, with and without waves, are also needed to understand subtle changes in the local wind, temperature, and cloud/haze structure.

This work used data from the NASA/ESA HST Space Telescope, and A.A.S., M.H.W., and G.S.O. were supported by grants from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with programs GO13067, GO13937/14334/14756/15262, GO14661, and GO14839. Jupiter maps are available from the MAST archive (OPAL, https://archive.stsci.edu/prepds/opal, doi:10.17909/T9G593; WFCJ, https://archive.stsci.edu/prepds/wfcj, doi:10.17909/T94T1H). RGC’s research was supported by an appointment to the NASA Postdoctoral Program at the NASA Goddard Space Flight Center, administered by Universities Space Research Association under contract with NASA. R.H., P.I. and A.S.-L. were supported by the Spanish MINECO project AYA2015-65041-P with FEDER, UE support and Grupos Gobierno Vasco IT-765-13. P.I. also acknowledges a PhD scholarship from Gobierno Vasco. L.N.F. was supported by a Royal Society Research Fellowship and European Research Council Consolidator Grant (under the European Union’s Horizon 2020 research and innovation programme, grant agreement No. 723890) at the University of Leicester. Observations at the Pic du Midi observatory were acquired by the Pic-Net team, F. Colas, M. Delcroix, E. Kraaijamp, R. Hueso, D. Peach, C. Spriau, G. Therin, with funding from Europlanet 2020 RI, which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 654208. We thank Dr. A. Ingersoll for a thorough review and useful comments.

Appendix
Large Data Set Information

Several larger data sets were analyzed in this work. Figures 10–13 provide full resolution views from several of the Hubble data sets. Ground-based images are shown in Figures 11–13. Table 5 includes a list of Voyager images where NEB waves were identified.
Figure 11. Cylindrical maps of the NEB based on images listed in Table 2. Blue lines show the start and end of the regions where waves are visible. The different wave systems are highlighted with a yellow line above the latitude of interest. All longitudes are given in System III and all latitudes are planetocentric. Dates are from February 22 to April 10.
Figure 12. Same as Figure 11 but for dates extending from April 16 to 26 with more observations due to the proximity to Jupiter opposition on April 6.
Figure 13. Same as Figure 11 but for dates extending from April 26 to June 13.
| Image ID              | Start time          | Filter |
|----------------------|---------------------|--------|
| J_IMG_VG2_ISS_2042242_N | 1979 Jun 26T00:49:35 | Green  |
| J_IMG_VG2_ISS_2042240_N | 1979 Jun 26T00:51:11 | Violet |
| J_IMG_VG2_ISS_2042248_N | 1979 Jun 26T00:52:46 | Orange |
| J_IMG_VG2_ISS_2042547_N | 1979 Jun 26T10:43:59 | Green  |
| J_IMG_VG2_ISS_2042549_N | 1979 Jun 26T10:45:35 | Violet |
| J_IMG_VG2_ISS_2042545_N | 1979 Jun 26T10:47:10 | Orange |
| J_IMG_VG2_ISS_20426712_N | 1979 Jun 26T20:39:59 | Green  |
| J_IMG_VG2_ISS_20426714_N | 1979 Jun 26T20:41:35 | Violet |
| J_IMG_VG2_ISS_20426716_N | 1979 Jun 26T20:43:10 | Orange |
| J_IMG_VG2_ISS_20428950_N | 1979 Jun 27T14:46:23 | Green  |
| J_IMG_VG2_ISS_20428952_N | 1979 Jun 27T14:47:59 | Violet |
| J_IMG_VG2_ISS_20428954_N | 1979 Jun 27T14:49:34 | Orange |
| J_IMG_VG2_ISS_2029201_N  | 1979 Jun 27T16:31:11 | Green  |
| J_IMG_VG2_ISS_2029203_N  | 1979 Jun 27T16:32:42 | Orange |
| J_IMG_VG2_ISS_2036474_N  | 1979 Jun 28T20:19:59 | Violet |
| J_IMG_VG2_ISS_2036494_N  | 1979 Jun 28T20:21:35 | Green  |
| J_IMG_VG2_ISS_2036514_N  | 1979 Jun 28T20:23:10 | Orange |
| J_IMG_VG2_ISS_2039172_N  | 1979 Jun 28T22:19:59 | Violet |
| J_IMG_VG2_ISS_2039192_N  | 1979 Jun 28T22:21:35 | Green  |
| J_IMG_VG2_ISS_2039292_N  | 1979 Jun 28T22:23:10 | Orange |
| J_IMG_VG2_ISS_2035250_N  | 1979 Jun 29T17:10:23 | Violet |
| J_IMG_VG2_ISS_2035252_N  | 1979 Jun 29T17:11:58 | Orange |
| J_IMG_VG2_ISS_2036413_N  | 1979 Jun 30T02:16:47 | Violet |
| J_IMG_VG2_ISS_2036415_N  | 1979 Jun 30T02:18:22 | Orange |
| J_IMG_VG2_ISS_2036531_N  | 1979 Jun 30T03:19:11 | Orange |
| J_IMG_VG2_ISS_2036533_N  | 1979 Jun 30T03:20:46 | Orange |
| J_IMG_VG2_ISS_2037604_N  | 1979 Jun 30T11:45:35 | Orange |
| J_IMG_VG2_ISS_2037606_N  | 1979 Jun 30T11:47:10 | Orange |
| J_IMG_VG2_ISS_2037616_N  | 1979 Jun 30T11:55:11 | Violet |
| J_IMG_VG2_ISS_2037618_N  | 1979 Jun 30T11:56:46 | Green  |
| J_IMG_VG2_ISS_2037900_N  | 1979 Jun 30T14:06:23 | Orange |
| J_IMG_VG2_ISS_2037902_N  | 1979 Jun 30T14:07:58 | Orange |
| J_IMG_VG2_ISS_2038392_N  | 1979 Jun 30T22:35:11 | Violet |
| J_IMG_VG2_ISS_2038393_N  | 1979 Jun 30T22:36:46 | Orange |
| J_IMG_VG2_ISS_2038940_N  | 1979 Jun 30T22:38:23 | Violet |
| J_IMG_VG2_ISS_2038941_N  | 1979 Jun 30T22:39:58 | Orange |
| J_IMG_VG2_ISS_2038942_N  | 1979 Jun 30T22:41:35 | Orange |
| J_IMG_VG2_ISS_2038946_N  | 1979 Jun 30T22:43:10 | Orange |
| J_IMG_VG2_ISS_2039105_N  | 1979 Jun 30T23:46:23 | Orange |
| J_IMG_VG2_ISS_2039107_N  | 1979 Jun 30T23:47:58 | Orange |
| J_IMG_VG2_ISS_2039109_N  | 1979 Jun 30T23:49:35 | Orange |
| J_IMG_VG2_ISS_2040208_N  | 1979 Jul 01T08:36:47 | Orange |
| J_IMG_VG2_ISS_2040214_N  | 1979 Jul 01T08:41:34 | Orange |
| J_IMG_VG2_ISS_2041654_N  | 1979 Jul 01T20:25:35 | Orange |
| J_IMG_VG2_ISS_2041656_N  | 1979 Jul 01T20:27:10 | Orange |
| J_IMG_VG2_ISS_2042837_N  | 1979 Jul 02T05:47:59 | Orange |
| J_IMG_VG2_ISS_2042841_N  | 1979 Jul 02T05:51:10 | Orange |
| J_IMG_VG2_ISS_2043811_N  | 1979 Jul 02T13:27:11 | Orange |
| J_IMG_VG2_ISS_2043813_N  | 1979 Jul 02T13:28:46 | Orange |
| J_IMG_VG2_ISS_2044103_N  | 1979 Jul 02T15:44:47 | Orange |
| J_IMG_VG2_ISS_2044105_N  | 1979 Jul 02T15:46:22 | Orange |
| J_IMG_VG2_ISS_2044107_N  | 1979 Jul 02T15:47:59 | Orange |
| J_IMG_VG2_ISS_2044109_N  | 1979 Jul 02T15:49:34 | Orange |
| J_IMG_VG2_ISS_2045110_N  | 1979 Jul 02T23:50:23 | Orange |
| J_IMG_VG2_ISS_2045112_N  | 1979 Jul 02T23:51:58 | Orange |
| J_IMG_VG2_ISS_2046324_N  | 1979 Jul 03T09:37:35 | Violet |
| J_IMG_VG2_ISS_2046328_N  | 1979 Jul 03T09:40:46 | Orange |
| J_IMG_VG2_ISS_2047650_N  | 1979 Jul 03T19:46:23 | UV     |
| J_IMG_VG2_ISS_2047607_N  | 1979 Jul 03T19:47:56 | Violet |
| J_IMG_VG2_ISS_2047617_N  | 1979 Jul 03T19:55:59 | Violet |
| J_IMG_VG2_ISS_2047619_N  | 1979 Jul 03T19:57:32 | UV     |
| J_IMG_VG2_ISS_2047625_N  | 1979 Jul 03T20:02:23 | Violet |
| J_IMG_VG2_ISS_2047627_N  | 1979 Jul 03T20:03:56 | UV     |

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