Infrared Detection of Waves in Jupiter's North Equatorial Belt

Sandra Wells
Universitat Politècnica de Catalunya - BarcelonaTech

Mentor: Dr. Glenn S. Orton
Jet Propulsion Laboratory, California Institute of Technology

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Abstract

Upper-tropospheric waves have found to be present in Jupiter's North Equatorial Belt (NEB) during and after a recent instance in which it expanded in latitude to the north. This is expected to be part of a cyclic series of such events. Although these visible expansion events are well documented, previously conducted surveys cannot conclude whether the upper-tropospheric waves were also present only during previous expansions, or whether they could be initiated by other dynamical phenomena. Tracking the appearance and variability of these waves during non-expansion periods is necessary in order to distinguish between possible hypotheses for their origin. A program to find the relative intensity of the upper-tropospheric NEB waves was implemented on a suite of images acquired at near-infrared wavelengths between 2.00 and 2.23 microns from 1995 to the present. Analyzing the temporal evolution of the intensity of these waves, using their variance from the mean, allows us to find the dates at which the waves present at the NEB are the most prominent, not only in their amplitude but also in their latitudinal span. A visual approach to wave characterization was used to check the results obtained with the program and to obtain further ones. The results obtained allow a cross-comparison between the dates at which the most intense waves appear and the dates at which NEB expansions or other planetary phenomena are recorded to have taken place, and therefore to establish (or disprove) a correlation between them. We found that the waves are also present at several dates outside of the NEB expansion periods, and that they could therefore be caused by other planetary phenomena. In particular, a specific type of these waves has been found to appear immediately after the two documented North Tropical Belt (NTB) jet disturbances in 2007 and 2016.

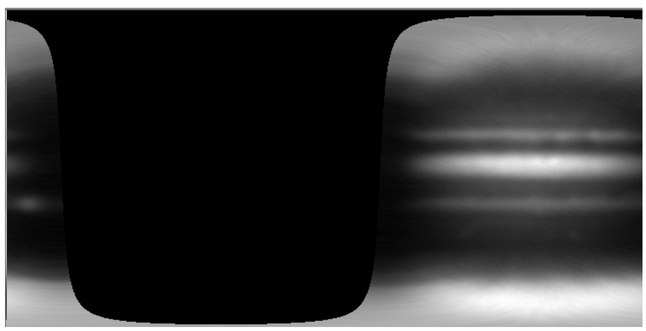
Introduction

The dynamics of Jupiter's atmosphere have long been a subject of study and still remain widely unknown to the scientific community. Expanding this knowledge is one of the main objectives of NASA's Juno mission. As a part of it, for the past few decades, the ground-based InfraRed Telescope Facility (IRTF) operated by the University of Hawaii for NASA has been acquiring images of Jupiter at near-infrared and infrared wavelengths. These images are of special interest because they provide information of higher layers of the atmosphere than those seen with optical wavelengths, thus helping understand more about Jupiter's vertical structure.

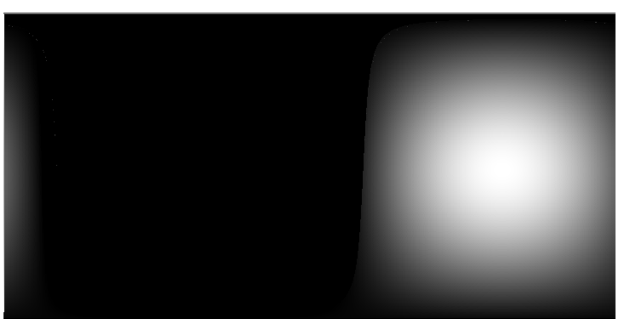
Fletcher et al. [1] have found upper-tropospheric waves to be present in Jupiter's NEB during and after the cyclic NEB expansion events on December 2000, June 2006, August 2009, August 2012, October 2012, and January 2016, leading to the hypothesis that there exists a correlation between these two phenomena. The goal of this work is to prove or disprove this hypothesis by tracking the appearance and variability of these waves from all useful data obtained by the IRTF in the past two decades. Furthermore, if no such correlation is found, the temporal variability and time of origin of the waves also allows to establish possible correlations with other atmospheric events.

Methods

The images used to find and analyze the NEB upper-tropospheric waves have been taken with NSFCam, NSFCam2 and SpeX, from 1995 to the present, at any of the individual near-infrared wavelengths: 2.00, 2.03, 2.07, 2.10, 2.12, 2.14, 2.16, 2.17, 2.20 and 2.23 μm. After the images have been acquired, they undergo the reduction process, which smoothens blemishes in individual files and eliminates the bad pixels as well as the contributions from the sky and the telescope itself in each planetary image. A cylindrical map of Jupiter is then obtained from each reduced image, thus facilitating the analysis of features at one same planetary latitude by projecting them at one same y-axis value. Mu and mu0 (emission and solar incidence angle cosines, respectively) backplane files are created together with each cylindrical map to take account for this projection. Figure 1 shows an example of these three files.



(a) Cylindrical map of Jupiter.



(b) Mu0 cylindrical map.

(c) Mu cylindrical map.

Fig 1: Files from December 14th 2016, 2.16 μm.

Two approaches have been used for finding and analyzing the waves in these images: a variance approach and a visual approach.

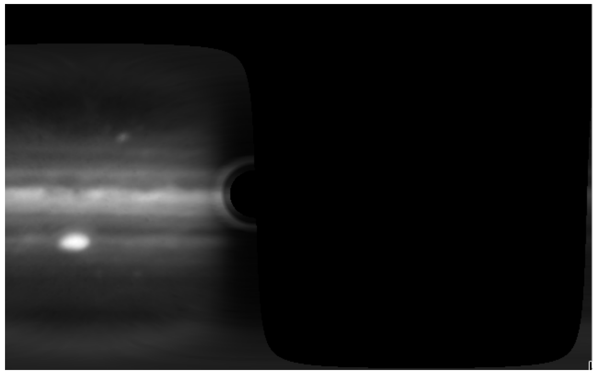
1. Variance approach

For this approach, an IDL program has been created, which finds and characterizes the upper-tropospheric NEB waves in each cylindrical map of Jupiter from a given list of files in the following way:

- Gets and reads a cylindrical map of Jupiter as well as its associated mu and mu0 maps. These are used to perform corrections to the intensity data in the cylindrical map as a function of emission angle or solar incident angle.
- For the latitude span corresponding to the NEB (14^o to 21^o N planetographic latitude) averages the observed intensity with respect to longitude, which notably reduces the noise present in the data.
- For longitudes at which intensity data is present, finds its mean I_{NEB}, rescales the data relative to it and finds its relative variance:
$$var_{rel} = \frac{1}{n}\sum_{i=1}^{n}\Big(\frac{I_i - I_{NEB}}{I_{NEB}}\Big)^2$$
where n is the number of points with present intensity data and I_i is the value of the intensity at each data point i.

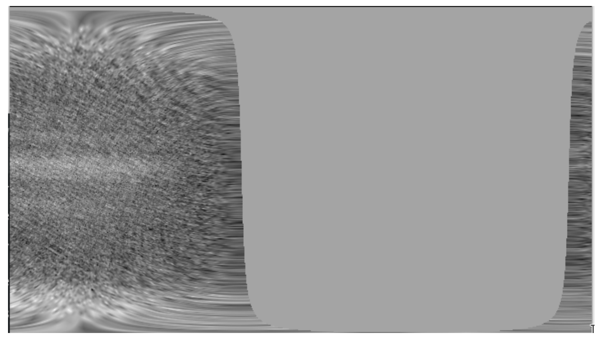
Applying this procedure to the 947 available (and useful) files acquired from 1995 to present allows us to find the temporal evolution of the variance of these waves, which essentialy characterizes the amplitude and/or latitudinal width of the waves. In order for the program to do this, a first step of uniformizing the size of the image (which is not constant through all years of data acquisition) is implemented, as well as a last step of extracting the observation date from the image header (the format of which is also not constant through all years of data acquisition).

The files mentioned above have been specified to be useful because of the fact that they have been selected from a longer list of files containing, in addition, files that are considered “problematic”. Figure 2 shows examples of the most relevant of these problematic files.

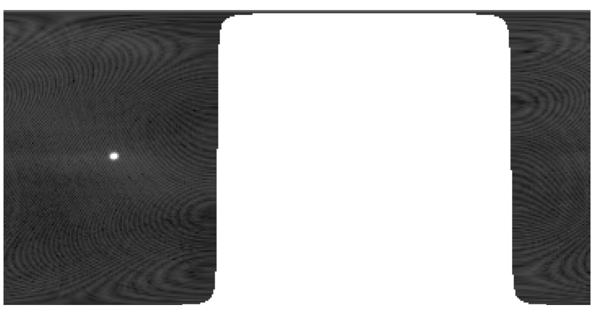


(a) July 1st 1996, 2.00μm. A region of Jupiter was outside of the telescope range during observation, leading to cutoff near NEB in cylindrical map.

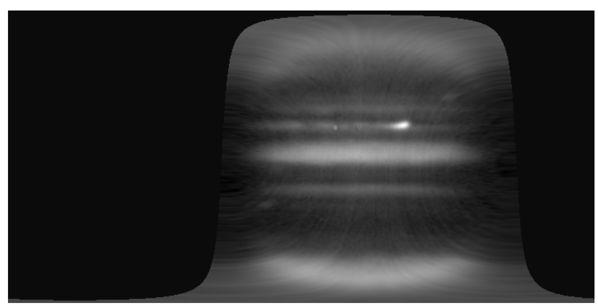
(b) April 23rd 2008, 2.07μm. One of Jupiter's satellites passing in front of NEB.



(c) November 24th 2015, 2.16μm. Very bad quality of image, likely due to bad weather conditions during observation.



(d) September 9th 2009, 2.16μm. White background.



(e) May 5th 2007, taken at 2.17μm. NTB outbreak. The study of this phenomena was published in Nature [2].

Fig 2: Because these problematic cylindrical maps of Jupiter give rise to very high relative NEB intensity variance values for reasons other than NEB waves, or do not contain valuable data, they cannot be used in this wave analysis procedure.

2. Visual approach

The images have been visually classified by using the following codes:

- No waves (-)
- Discrete features (B)

In order to classify the images showing waves-like features, these have been characterized using a three-letter code, as follows:

1. Strength of wave: low (L) / medium (M) / high (H)
2. Type of wave: width (W) / intensity (I) / combination (C)
3. Longitudinal coverage: full (F) / partial (P)

Figures 3 to 7 show examples of each of these distinctions.

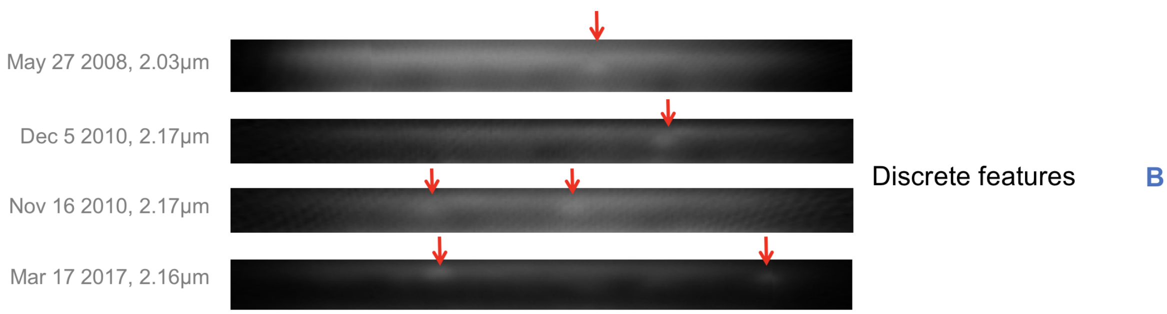


Fig 3: NEB images showing no wave-like features.

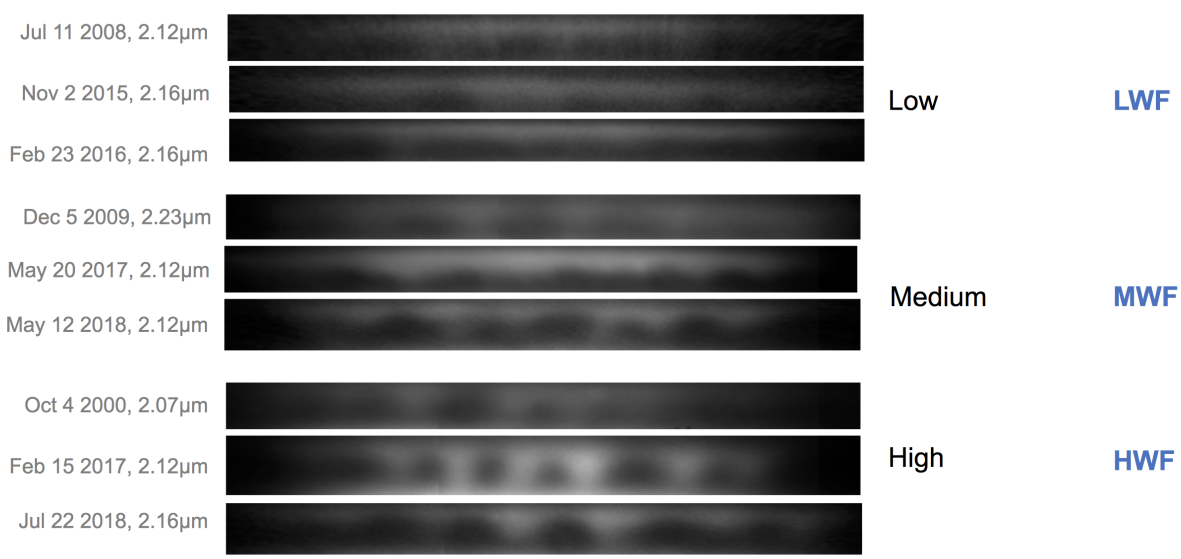


Fig 4: Strength classification of width-type, full longitudinal coverage waves. The predominant oscillation in this type of waves takes place in the width of the NEB.

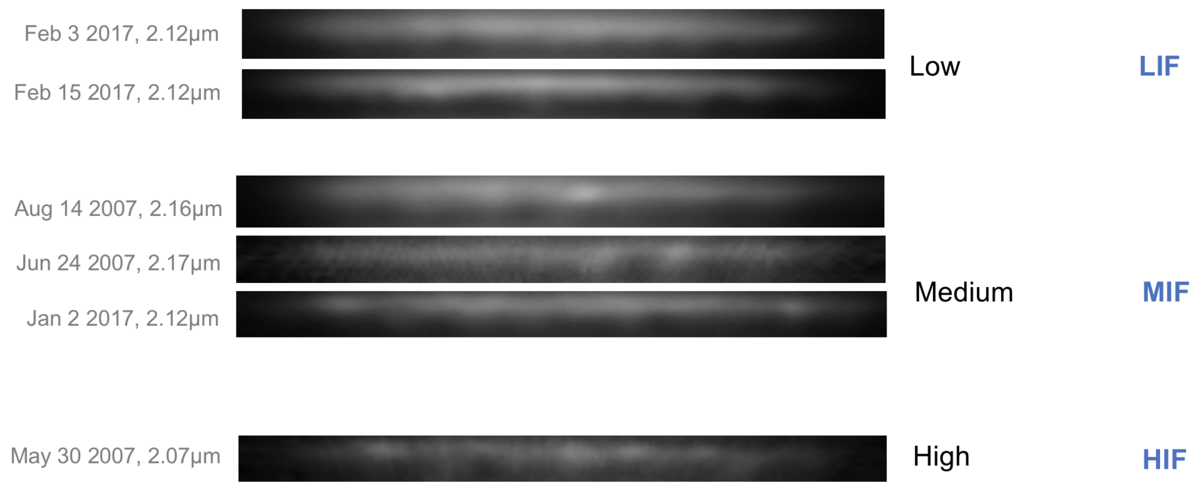


Fig 5: Strength classification of intensity-type, full longitudinal coverage waves. The predominant oscillation in this type of waves takes place in the brightness of the NEB. (Although the image classified as HIF might seem weaker than those classified as MIF, the full cylindrical map has a much lower contrast, which justifies why its oscillation is actually stronger.)

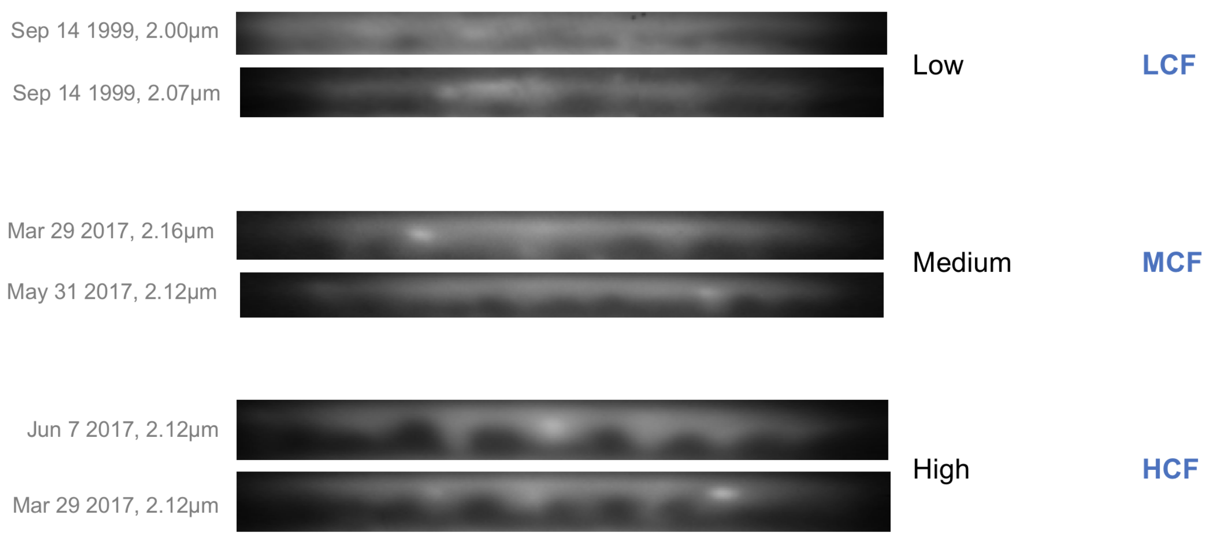


Fig 6: Strength classification of combination-type, full longitudinal coverage waves. The oscillations in both the width and the brightness of the NEB are prominent.

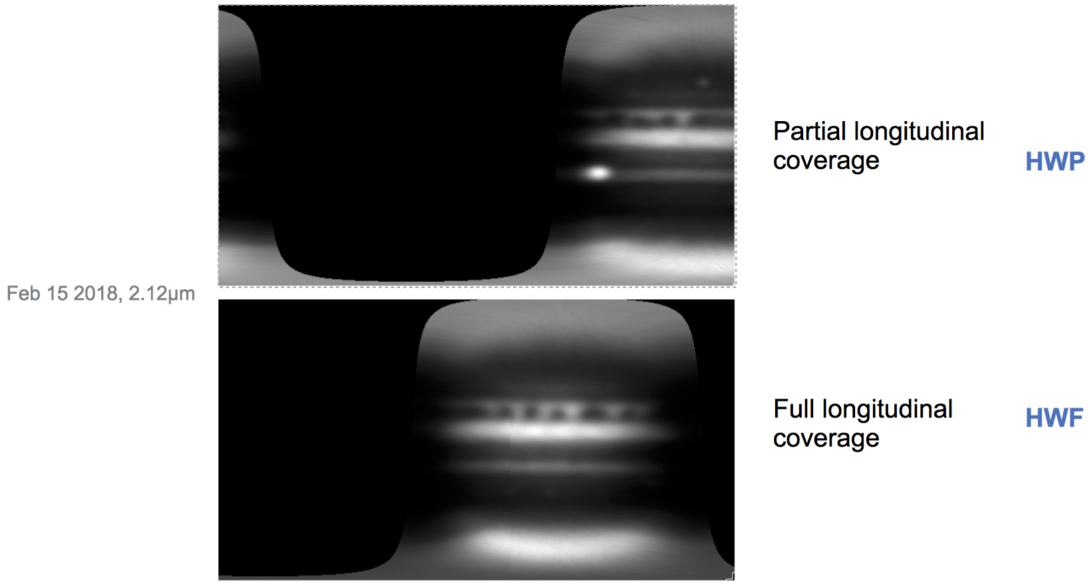


Fig 7: Longitudinal coverage classification: for one same date, the top image shows a wave only partially in its longitudinal span, while it is present in the full longitudinal coverage of the bottom image.

The visual approach is useful, first, to check that the results obtained with the variance approach correspond to what can actually be seen in each image. And, second, the visual classification can be represented graphically to show the evolution of the strength, type and longitudinal span of the waves (or discrete features) in time.

Results and discussion

The results obtained from the variance approach are shown in figure 8.

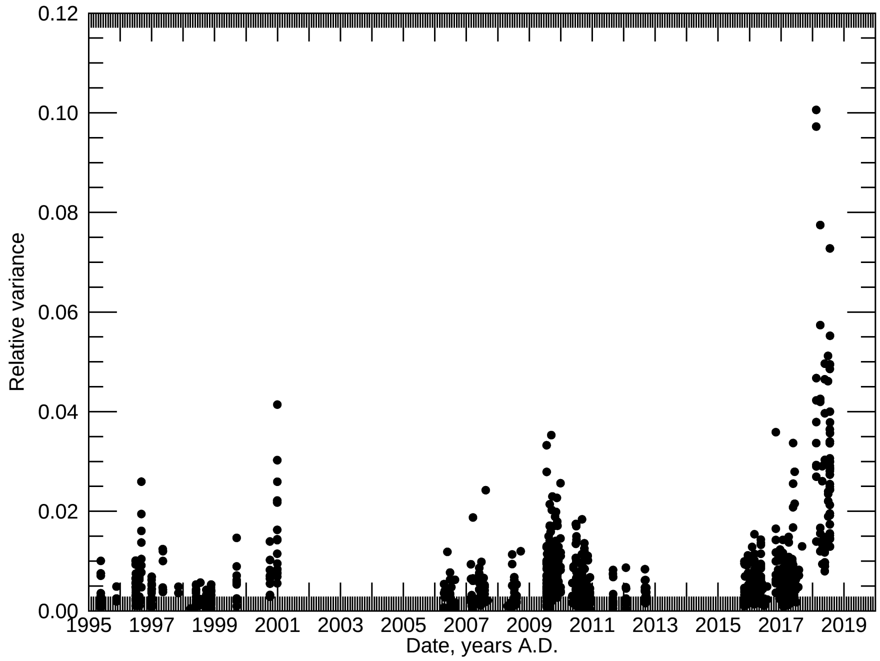
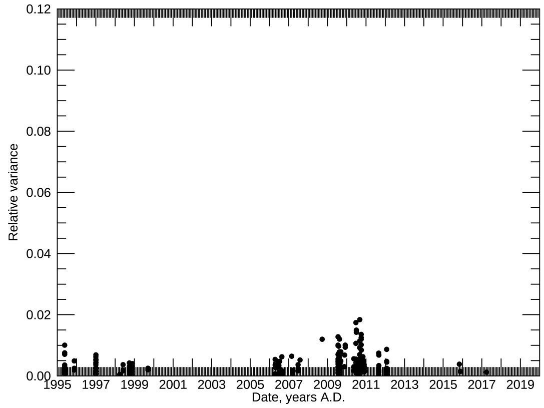
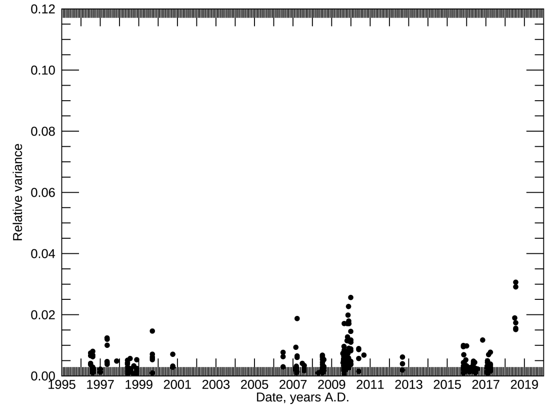


Fig 8: Relative intensity variance found in Jupiter's NEB as a function of the date of observation.

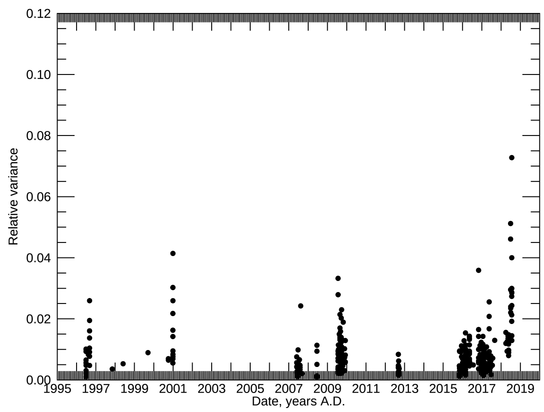
In order to check that these variance results are proportional to the waves observed in the pictures, these results have been obtained for each separate observed strength, as shown in figure 9.



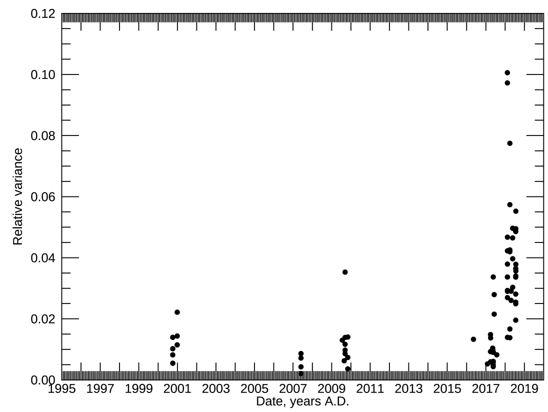
(a) No waves



(b) Low-strength waves



(c) Medium-strength waves



(d) High-strength waves

Fig 9: Relative intensity variance found in Jupiter's NEB as a function of the date of observation, represented separately for images visually classified as containing no waves, low-, medium- or high-strength waves.

Figure 9 shows that, while the variance peaks are higher in images with waves of higher observed strength, there is not a direct relationship between the observed strength of a wave and its value obtained through the relative variance procedure. For this reason, this procedure should be studied and improved or simply discarded as an approach to this study.

The results obtained from the visual approach are represented in figures 10 and 11. Because, although subjective, these results are trustworthy, they have been superposed to the NEB expansion timeline, as documented by Fletcher et al. [1].

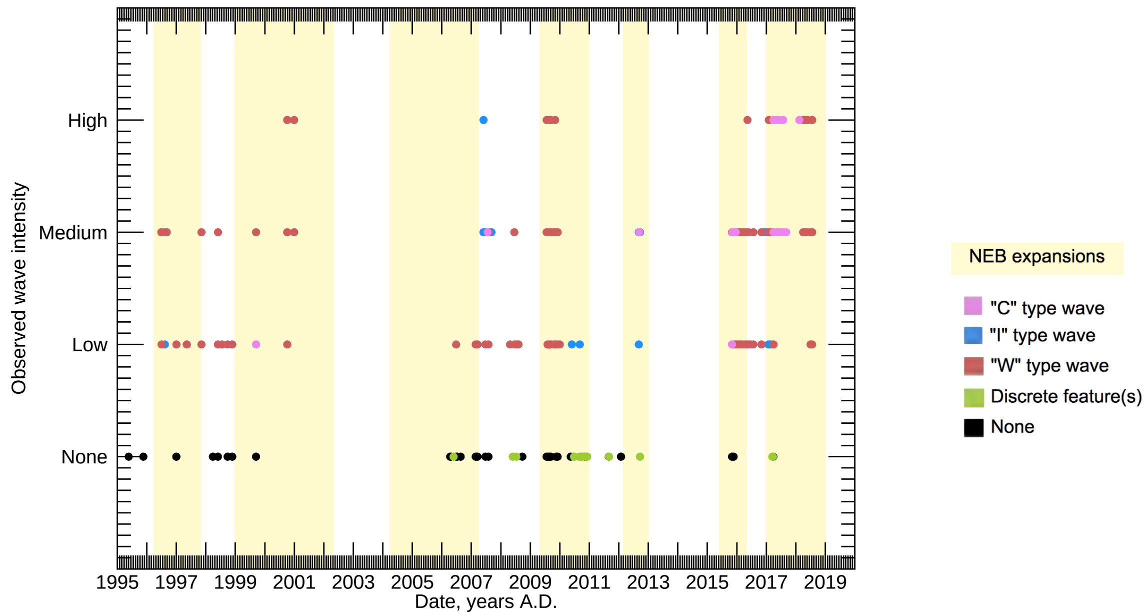


Fig 10: Visual classification of waves, represented analogously to the variance approach results. The wave strength is represented in the y-axis, while colors distinguish between different types of waves or discrete features.

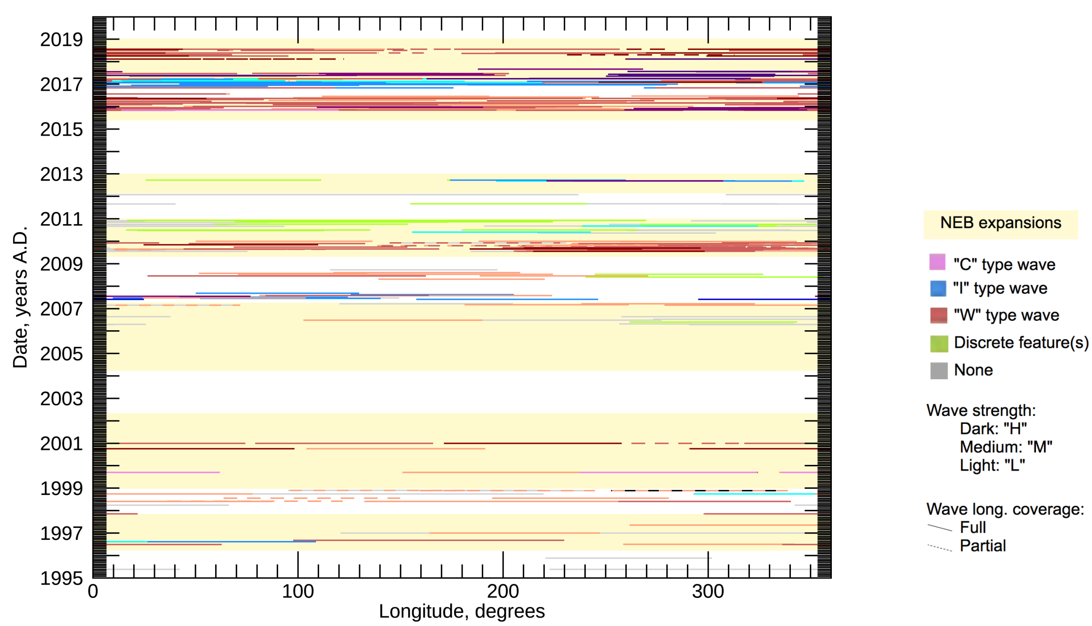


Fig 11: Alternative representation of the visual wave classification, the date now ascending along the y-axis and the x-axis indicating the planetary longitudes of Jupiter at which the wave is observed. The type of wave or feature is again indicated by its color, the strengh by its darkness and longitudinal coverage by line continuity.

From figure 10 we can determine that:

- Upper-tropospheric NEB waves are present during all NEB expansion periods, but also in 1998, 2008 and early 2016, where no NEB expansions were taking place.

Figure 11 makes it easier to further analyze the results, showing that:

- Intensity-type waves are found to be present after the two recorded outbreaks in Jupiter's NTB in May 2007 and October 2016.
- Waves do not all occur at one same longitudinal region.
- The majority of documented discrete features appear in 2010.

Conclusions

The most relevant of our results are, first, that the waves are present outside of the documented NEB expansion periods. This could disprove a correlation between the two phenomena, although more temporal and longitudinal coverage would be necessary in the graphical results in order to state this with certainty. And, second, that strong oscillations in the near-IR intensity of the NEB are found immediately after the two recorded NTB outbreaks [2], [3], which could very well mean that intensity-type waves are caused by these jet disturbances. Again, further temporal and longitudinal coverage would be helpful in determining this with certainty, by possibly assuring that these waves are not present at other times.

Regarding the temporal coverage, it is clear from figures 8 to 11 that there are two major gaps: early 2001 to 2006 and late 2012 to late 2015. While the second one is due to NSFCam2 not being operational, the first can be solved by using more files that have not been used in this work because they had not yet been reduced and/or cylindrically projected. A list of all these files has been created for future students to process and add to the study. This list includes files from outside this temporal gap as well, which will help extract more information from the graphical results.

Acknowledgements

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References

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[2] Agustín Sánchez-Lavega, Glenn S. Orton, Ricardo Hueso, Enrique Garcia-Melendo, Santiago Perez-Hoyos, Amy A. Simon-Miller, Joshua Rojas, José M. Gómez, Padma A. Yanamandra-Fisher, Leigh N. Fletcher, J. Joels, J. Kemerer, Joe Hora, Erich Karkoschka, Imke de Pater, Michael H Wong, Philip S. Marcus, Noemí Pinilla-Alonso, Filipe Gusmão Carvalho, Cristina Go, Douglas M. Parker, Matthew Salway, M. Valimberti, Annie S. Wesley, and Zac Pujic. Depth of a strong Jovian jet from a planetary-scale disturbance driven by storms. *Nature*, 451:437–440, 2008.

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