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Longitudinal variability in Jupiter's zonal winds derived from multi-wavelength HST observations☆

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ABSTRACT

Multi-wavelength Hubble Space Telescope (HST) images of Jupiter from the Outer Planets Atmospheres Legacy (OPAL) and Wide Field Coverage for Juno (WFCJ) programs in 2015, 2016, and 2017 are used to derive wind profiles as a function of latitude and longitude. Wind profiles are typically zonally averaged to reduce measurement uncertainties. However, doing this destroys any variations of the zonal-component of winds in the longitudinal direction. Here, we present the results derived from using a "sliding-window" correlation method. This method adds longitudinal specificity, and allows for the detection of spatial variations in the zonal winds. Spatial variations are identified in two jets: 1 at 17°N, the location of a prominent westward jet, and the other at 7°S, the location of the chevrons. Temporal and spatial variations at the 24°N jet and the 5-μm hot spots are also examined.

1. Introduction

Jupiter's banded appearance at visible wavelengths has been observed for centuries. Alternating light and dark regions encircle the planet, creating parallel zones and belts each roughly 10° in width, with the pattern observed at all latitudes visible from ground-based telescopes. Strong zonal (east-west) jets exist at the interfaces between zones and belts. Historically, the jets were discovered by feature tracking (Peek, 1958; Beebe et al., 1980; Limaye, 1986). With this method, two time-separated images are compared. The location of a cloud or some identifiable discrete feature is recorded in both images, and the longitudinal difference between the two locations is found. This displacement Δx, along with the time difference Δt between the two images allows for the simple calculation of the feature's zonal velocity, u.

There have been previous attempts to identify spatial and temporal variations in Jupiter's winds, with major results primarily limited to the jets near 24°N and 7°N. Simon (1999) analyzed several data sets including Voyager, Galileo, and several years of HST observations using the same process on each to ensure consistency. She identified temporal variations at the 24°N, 6°S, and 20°S jets, and found the speed changes to be correlated with surface brightness and in some cases also with cloud structure changes. Asay-Davis et al. (2011) reported a decrease in wind speed at 24°N as the only detected change in the zonal wind profile (ZWP) between 2000 and 2008 in their Cassini and HST data sets. Asay-Davis et al. (2011) also compared two zonal wind extraction techniques, designated "global" and "local", to look for spatial variations. They found disparities in the zonal wind from the two techniques at 8°N, and concluded that their global method was finding the drift velocity of the hot spots while the local method was finding the true cloud-level velocity. Other variability studies include, for example, Sánchez-Lavega et al. (2008), Simon-Miller and Gierasch (2010), and Barrado-Izagirre et al. (2013).

Recently, Tollefson et al. (2017) and Hueso et al. (2017) used similar ZWP extraction techniques on some of the same data as this study. Hueso et al. (2017) compared ZWPs created using ground-based data to those they created from the February 2016 631-nm Outer Planets Atmospheres Legacy (OPAL) data. They concluded that there were no statistically significant differences between the two profiles. Additionally, they

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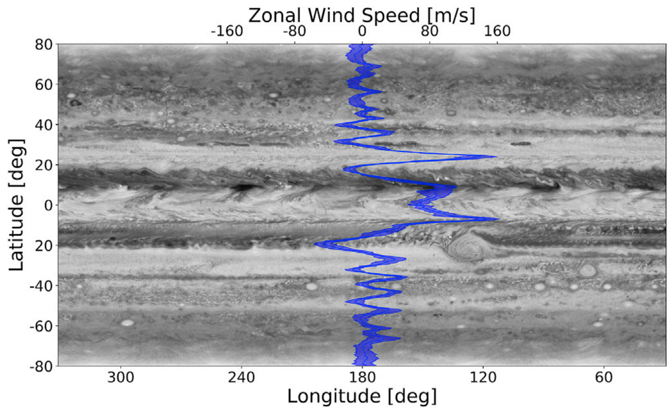

Fig. 1. Map of the Jovian atmosphere taken on 19 January 2015 using HST in the 631-nm filter, with the ZWP for 2015, also from the 631-nm filter, overlaid. The shading represents the uncertainty, which is the standard deviation of regional profiles that were used to create the mean ZWP.

compared their OPAL profile to Cassini flyby data from 2000. Temporal differences between these two profiles were limited to the 24°N jet, the location of the 5-μm hot spots, and the South Equatorial Belt jet at 7°N. They linked these differences to the development of large-scale convective disturbances, slow hot spot drift rates, and a wave system observed in 2015, respectively. Tollefson et al. (2017) used a 1-dimensional correlation technique to derive ZWPs from HST data sets (including 2015 and 2016 OPAL data) spanning from September 2009 to December 2016. They identified temporal changes in several jets, including three that are also analyzed in this work (24°N, and the two equatorial jets near ± 7°), citing similar reasons as Hueso et al. (2017) for these variations.

To facilitate the discussion regarding Jupiter's wind profile, in Fig. 1, we plot the average ZWP that we obtain later on in this paper on top of a planisphere of Jupiter. The wind profile is characterized by strong eastward jets at the equator, flanked by westward jets, with jets continuing this alternating pattern to the poles. The equatorial region features a "double-horned" structure with eastward jets of 100 ms^{-1} and 150 ms^{-1} at 7°N and 7°S[1], respectively. The fastest jets have peaks around 24°N and 7°S, with eastward velocity of 150 ms^{-1}. The strongest westward jet is at 20°S with a velocity of $-50\ ms^{-1}$. The other jets have speeds of $\sim 50\ ms^{-1}$ or slower. All surveys have found very little meridional motion of Jupiter; the bulk zonal flow is orders of magnitude greater than the meridional flow. Ingersoll et al. (1981) derived meridional velocity profiles from Voyager 1 and 2 data, with speeds of less than 10 ms^{-1} at all latitudes.

In contrast to Earth's atmospheric structure, Jupiter's zonal flows are remarkably constant in time. For example, Asay-Davis et al. (2011) compared zonal profiles created from Voyager-2, Cassini, and HST data sets, spanning over three decades, and found only a few statistically significant changes to the latitude location or wind speed of all of the major jets. Ingersoll et al. (1981) also found the zonal velocity to be constant to within 1.5% between the two Voyager encounters, and more recently Hueso et al. (2017) reported minimal temporal changes when comparing 2016 HST data with 2000 Cassini flyby data. This consistency over long timescales implies a mechanism for counteracting or minimizing the effects of friction and dissipation. Additionally, the zonal wind at a given latitude is nearly constant at all longitudes. Variations from the zonal mean flow do exist, however they have not been well-studied, primarily due to the difficulty in extracting reliable regional profiles from observations rather than the zonal average. The most well-studied region for longitudinal variations is the North Equatorial Belt's 5-μm hot spots (see Asay-Davis et al. (2011) and García-Melendo et al. (2011), for example).

[1] All velocities and longitudes reported here are relative to System III, which corresponds to a rotation period of $9^h55^m29^s.711 \pm 0^s.04$ (Riddle and Warwick, 1976). All latitudes are planetographic.

Here, we present zonal wind analysis of HST images from 2015, 2016, and 2017 that show measurable longitudinal variations. Section 2 begins with a description of the HST observations used for this analysis. The one-dimensional ZWP derivation technique is then described, including a detailed explanation of the uncertainty estimation. The results from this analysis are presented in Section 3. In particular, we focus on several latitude regions where temporal and/or longitudinal variations were evident, including 7°S, 7°N, 17°N, and 24°N.

2. Methods

2.1. Observations

Four HST data sets were used for the analysis, three of which were part of the OPAL program (Simon et al., 2015). These were taken on 19 January 2015, 9/10 February 2016, and 3 April 2017, and each consist of two consecutive full Jupiter rotations. Eight filters were used in 2015, while nine were used in both 2016 and 2017, covering UV (275-nm) to near-IR (889-nm) wavelengths. Some wavelengths were poorly suited for ZWP derivation because of a lack of contrast. Details of the filters used in each set of observations is given in Table 1.

A fourth HST data set was also used. These images were taken on 11 December 2016, and are referred to here as 2016b. The observations were done as part of the Wide Field Coverage for Juno program (GO-14661) with the goal of providing the UV/optical imaging context for Juno atmospheric measurements, including global velocity fields for some of the spacecraft passes. Zonal winds have been derived separately from this December 2016 dataset and are presented by Tollefson et al. (2017). This data set was analyzed here using an identical process to the OPAL data sets.

The HST images were de-projected into image maps, each spanning 80° in latitude by 80° in longitude. Individual maps were used rather than a mosaic map of the entire atmosphere because the timing of the individual maps is better known, and the time difference between two images is necessary to derive the wind speed. Consecutive maps in one filter overlapped in longitude, by around 40°, and were typically separated by roughly ten hours (one Jovian rotation). The resolution was 0.1° per pixel in latitude and longitude.

A major advantage of this study is the OPAL data set's consistency. We have two consecutive rotations for each observation, which is essential for feature tracking methods. Additionally, the yearly observation timeline allows for the detection of temporal variations on time scales as small as a year, and these yearly observations will continue for the remainder of HST's lifetime. No previous study has a data set with this amount of consistency, which makes this and future analyses uniquely suited to identify variations in the zonal wind.

2.2. Profile extraction technique

The primary method for discovering deviations from the zonal mean is by a comparison of different profiles, i.e., the profile from one time

Table 1
Dates and filter information of the data sets used for the wind analysis presented here. Filters in the red optical region (631- and 658-nm) maximize both contrast (deeper penetration due to reduced Rayleigh scattering compared to blue) and resolution (which is inversely proportional to wavelength), which makes them the ideal filters for velocity measurements. The 275-, 343-, and 889-nm filters were excluded due to insufficient contrast, which led to spurious tracking and unreliable ZWPs. The 225-, 727-, and 750-nm filters were excluded since they were only used in one observation and therefore offered no comparative value. The 547-nm filter had to be excluded due to insufficient image overlap or problems with the navigation of the images.

Dates	Filters Included (nm)	Filters Excluded (nm)
January 19, 2015	395, 502, 631, 658	275, 343, 547, 889
February 9/10 2016	395, 467, 502, 631, 658	275, 343, 547, 889
December 11, 2016	395, 502, 631	225, 275, 343, 727, 750, 889
April 3, 2017	395, 467, 502, 631, 658	275, 343, 547, 889