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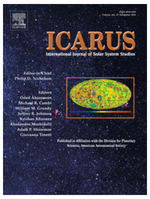

Changes in Jupiter's Zonal Wind Profile preceding and during the *Juno* mission

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ABSTRACT

We present five epochs of WFC3 HST Jupiter observations taken between 2009–2016 and extract global zonal wind profiles for each epoch. Jupiter's zonal wind field is globally stable throughout these years, but significant variations in certain latitude regions persist. We find that the largest uncertainties in the wind field are due to vortices or hot-spots, and show residual maps which identify the strongest vortex flows. The strongest year-to-year variation in the zonal wind profiles is the 24°N jet peak. Numerous plume outbreaks have been observed in the Northern Temperate Belt and are associated with decreases in the zonal velocity and brightness. We show that the 24°N jet peak velocity and brightness decreased in 2012 and again in late 2016, following outbreaks during these years. Our February 2016 zonal wind profile was the last highly spatially resolved measurement prior to *Juno*'s first science observations. The final 2016 data were taken in conjunction with *Juno*'s perijove 3 pass on 11 December 2016, and show the zonal wind profile following the plume outbreak at 24°N in October 2016.

1. Introduction

The most striking feature of Jupiter is its banded structure, home to swaths of bright, colorful clouds and immense vortices. The observed zonal flow, defined as the longitudinal average of the east-west winds in the visible cloud deck, is one of the most fundamental constraints on the circulation of Jupiter's atmosphere (Ingersoll et al., 2004). Jupiter's zonal wind profile (ZWP) has been a subject of intense study since the Voyager missions. Despite regular derivations of Jupiter's ZWP over the past 30 years, listed in Table 1, the winds have remained remarkably stable, with speeds up to 150 ms^{-1} and with variability on the order of 10 ms^{-1}. In contrast, the clouds of Neptune have displayed evidence of peculiar dynamics ever since Neptune's ZWP was first derived from Voyager 2 data (Limaye and Sromovsky, 1991). In particular, individual bright cloud features on Neptune can move with velocities more than 100 ms^{-1} off the Voyager-derived ZWP (Sromovsky et al., 1993; Martin et al., 2012; Fitzpatrick et al., 2014; Tollefson et al., 2017). What drives Jupiter's stable zonal flow, characterizing the magnitude and timescale of variability (if any) in Jupiter's jet peaks, and predicting how the zonal flow changes with depth remain outstanding questions today.

Three primary methods are used to directly calculate Jupiter's ZWP: 1D correlation, 2D correlation, and discrete feature tracking. In addition, the zonal winds may be indirectly determined by using the thermal wind relationship (Gierasch et al., 1986; Flasar et al., 2004; Simon et al., 2015). 1D correlation methods compute the zonal velocity by calculating longitudinal correlations of the clouds between sets of image pairs in a mosaic, typically in narrow latitude windows, but along a large range of longitudes. This method is insensitive to the north-south component of the velocity field,

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Table 1
Compilation of derived Zonal Wind Profiles for Jupiter. 'Global' describes either the 1D or 2D correlation methods, while 'Local' describes feature tracking.

Timespan (years)	Facility	Appx. Sub-observer Resolution (km/pixel)	Method	References
1979	Voyager 1 & 2 ISS	100	Local	Ingersoll et al. (1981)
			Local	Limaye et al. (1982)
			Global	Limaye (1986)
1995–2000	HST WFPC2	140	Global	García-Melendo and Sánchez-Lavega (2001)
2000	Cassini	120	Global	Porco et al. (2003)
			Local	Li et al. (2004)
			Local	Li et al. (2006)
2007	HST WFPC2	160	Global	Cheng et al. (2008)
2008	HST WFPC2	160	Global	Asay-Davis et al. (2011)
2011	PVOL/IOPW	380	Global	Barrado-Izagirre et al. (2013)
2009–16	HST WFC3	130	Global	This work

but meridional velocities are generally small when intense vortices are absent. The 1D correlation method is favored for its computational efficiency, and it reduces uncertainties due to bad pixels and random errors (Asay-Davis et al., 2011).

The 2D correlation method involves computing full horizontal flow fields, and averaging the east-west components over longitude to obtain the zonal velocity. This method has the advantage that longitudinal variations in the zonal winds are preserved and north-south velocities can be measured in high spatial resolution data. This is particularly important for obtaining accurate zonal wind measurements of the dark projections (associated with the 5 µm hotspots) at 8°N, whose velocities do not move with the true zonal flow at the visible cloud deck (Ortiz et al., 1998; Arregi et al., 2006; García-Melendo et al., 2011; Asay-Davis et al., 2011).

Discrete tracking methods determine zonal velocities by tracking large-scale features over long periods of time to generate one-dimensional or two-dimensional velocity fields. These fields are then averaged over their east-west components to give the mean zonal wind speed in a particular latitude bin.

'Global' correlation methods is an umbrella term to describe both 1D and 2D correlation methods – each utilize correlations at all longitudes of Jupiter. In contrast, feature tracking is often localized to longitude regions containing high-contrast trackable features. In data at low spatial resolution, including even amateur data, global methods can be used by combining results from multiple image pairs (Barrado-Izagirre et al., 2013; Hueso et al., 2017).

Among the past three decades of Jupiter ZWP derivations at the visible cloud deck, minimal wavelength dependence has been found (García-Melendo and Sánchez-Lavega, 2001), in contrast to the case for Saturn (Sánchez-Lavega et al., 2016; Pérez-Hoyos and Sánchez-Lavega, 2006). Images of Jupiter in the ultraviolet have been made to determine zonal wind profiles above the visible cloud deck (Li et al., 2006). Thus, all observations listed in Table 1, with the exception of Li et al. (2006), probe the same cloud vertical levels and any changes in the ZWP reflect temporal changes in Jupiter's atmosphere. Under this assumption, we derive ZWPs to examine changes in the 2009–2016 period, using data acquired with the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST). We use the 1D method to derive ZWPs, but also measure 2D velocity residuals from these mean profiles, preserving information on small vortex circulation, turbulence, and waves. The February 2016 ZWP is the last one measured from high spatial resolution data prior to *Juno*'s first science observations at perijove 1 (PJ1), which took place 27 August 2016 (Bolton et al., 2017). We also present a ZWP taken coincident to perijove 3 (PJ3), which occurred on 11 December 2016.

2. Description of observations

We derive zonal velocities from multiple HST image sets taken with the WFC3 from 2009 to 2016. The sub-observer pixel resolution of these images ranged from ∼ 130 km/pixel at opposition to 170 km/pixel at the PJ3 perijove distance of 5.85 AU. Table 2 gives details of each dataset, including filters, number of images used, and times of each image. We perform analysis on filters at red optical wavelengths to optimize feature contrast. Contrast can be reduced at shorter or longer wavelengths, due to Rayleigh scattering and/or haze reflectivity.

We collected data from four different WFC3 programs. The 2009 dataset was the first global mapping effort with WFC3 after it was installed in Hubble's final servicing mission. At opposition, Jupiter easily fits within a WFC3 2K subarray. Subarrays greatly increase duty cycle efficiency for WFC3 observations, because the instrument buffer can only hold two full frame (4K × 4K) exposures. But instrument modes were limited in WFC3's first observing cycle, so the only way to read out subarrays was to use quad filters (Wong et al., 2010). To increase HST scheduling flexibility, the 2009 observations imaged two hemispheres separately, one on 18–19 September, and the other on 22–23 September (Table 2). Fig. 1 shows a combined map of the two hemispheres, with the derived zonal wind profile overlaid (discussed in the following section).

The 2012 dataset (Fig. 2) was proposed as an attempt to measure a photometric dimming from the shadow of Venus, during a solar transit event as seen from Jupiter. The transit signal itself was never observed, due to the much greater contribution from horizontal inhomogeneity in Jupiter's lightcurve (Karalidi et al., 2015). The choice of a medium bandwidth filter (F763M) to image Jupiter's bright disk necessitated the shortest WFC3/UVIS integration time (0.48 s).[1]

Datasets from 2015 and early 2016 are part of the Outer Planet Atmospheres Legacy (OPAL) program (Simon et al., 2015). This program observes each of the giant planets at an annual cadence, for long-duration time-domain studies of storm activity, wind field variability, and changes in aerosol distributions and spectral properties. The program, which began in 2014, has led to discoveries of a new dark vortex on Neptune (Wong et al., 2016), rare wave phenomena on Jupiter (Simon et al., 2015), and new insights into variable cloud features on Uranus (Wong et al., 2015b; Irwin et al., 2017). The 2015 and 2016 global maps and zonal wind profiles are shown in Figs. 3 and 4 respectively.

The December 2016 dataset is part of the Wide Field Coverage for Juno (WFCJ) program. This program is synchronized with peri-

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[1] In short exposures, the WFC3/UVIS shutter introduces an expected variability of about 2% in exposure time (Hilbert, 2009), which should have dwarfed the predicted 0.01% signal (Pasachoff et al., 2013) from the Venus transit. However, the observed lightcurve seemed to be stable against shutter non-repeatability to within 1 part per thousand. This result raises the possibility that the Hilbert (2009) shutter repeatability analysis may have been limited by lower signal-to-noise ratio, compared to the very high signal-to-noise ratio of the Karalidi et al. (2015) Jupiter lightcurve, which integrated the flux over the full planetary disk.