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# Uranus' southern circulation revealed by Voyager 2: Unique characteristics

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ABSTRACT

Revised calibration and processing of 1600 images of Uranus by Voyager 2 revealed dozens of discrete features south of −45° latitude, where only a single feature was known from Voyager images and none has been seen since. Tracking of these features over five weeks defined the southern rotational profile of Uranus with high accuracy and no significant gap. The profile has kinks unlike previous profiles and is strongly asymmetric with respect to the northern profile by Sromovsky et al. (Sromovsky, L.A., Fry, P.M., Hammel, H.B., de Pater, I., Rages, K.A. [2012]. Icarus 220, 694–712). The asymmetry is larger than that of all previous data on jovian planets. A spot that included the South Pole off-center rotated with a period of 12.24 h, 2 h outside the range of all previous observations of Uranus. The region between −68° and −59° latitude rotated almost like a solid body, with a shear that was about 30 times smaller than typical shears on Uranus. At lower latitudes, features were sheared into tightly wound spirals as Voyager watched. The zone at −84° latitude was exceptionally bland; reflectivity variations were only 18 ppm, consistent with a signal-to-noise ratio estimated at 55,000. The low noise was achieved by smoothing over dozens of pixels per image and averaging 1600 images. The presented data set in eight filters contains rich information about temporal evolution and spectral characteristics of features on Uranus that will be the basis for further analysis.



## 1. Introduction

On the jovian planets, winds blow mostly eastward or westward, similar throughout each zone. The wind speed or rotational period as function of latitude characterizes the circulation of the planet. The first data point on the circulation patterns of the jovian planets was Jupiter's Great Red Spot tracked by Cassini in 1665. Further observations established Jupiter's and Saturn's eastward equatorial jets. Voyager 1 and 2 provided large data sets between 1979 and 1989. The spacecraft Galileo and Cassini, as well as the Hubble Space Telescope (HST) and ground-based telescopes complemented data since. Today, we know most of the four, jovian circulation profiles through tracking features at visible or near-infrared wavelengths.

Profiles have remained remarkably constant (e.g. Simon-Miller and Gierasch, 2010 for Jupiter, García-Melendo et al., 2011 for Saturn, and Sromovsky et al., 2012 for Uranus). Most noticeable was a decrease of Saturn's equatorial jet (Barnet et al., 1992). Some areas have a measured wind speed variation with altitude (e.g. García-Melendo et al., 2011 for Saturn). In this work, we do not focus on variations with time or altitude, but on latitudinal coverage.

Jupiter's and Saturn's profiles are completely known except for small gaps close to poles due to poor observing geometries (Fig. 1). Uranus' and Neptune's coverage is ∼75% with large gaps south of −45° latitude for Uranus and north of +45° for Neptune.

The large gaps have different reasons. Neptune's sub-solar latitude has been close to −30° for many decades (cf. Fig. 1), which has made the region north of 45° unobservable or too foreshortened to track features. On the other hand, Uranus southern latitudes have been imaged thousands of times with great geometry, but Uranus seems to be bland south of −45° latitude.

The observing geometry for Neptune's gap is improving but Uranus' gap will remain in darkness for several decades (Fig. 1). During the next decades, Neptune's gap can be filled with new observations, but filling Uranus' gap can only be done with past data. Uranus' profile also has a small gap north of 78° latitude that is due to poor observing geometry during the past decades, but this area is just getting well observable.

Voyager 2 imaged Uranus near its 1985 winter solstice with unsurpassed spatial resolution. Images showed seven discrete features, an order of magnitude less than for other Voyager fly-bys of jovian planets (Smith et al., 1986). Their Fig. 8 summarizes the

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Voyager rotational profile. It contains eight data points since one large feature was centered at two different latitudes in different filters. The single feature south of −45° latitude was weak. It was mentioned at −70° latitude with a 14.2 h rotational period, but plotted at −71° with a 14.3 h period (if these latitudes are planetocentric, they correspond to −71° and −72° planetographic that are used in this work). No discrete feature south of −45° latitude has been seen since.

The first HST images of Uranus were almost bland (Hammel, 1997; Karkoschka, 1997). Later images at wavelengths beyond 1 μm revealed features of high contrasts (Karkoschka, 1998). Adaptive optics at Keck captured features from the ground (Sromovsky et al., 2000; Sromovsky and Fry, 2005) and has provided most circulation data since. The data suggest a smooth rotational profile with a slow-rotating equator and fast-rotating high latitudes (Sromovsky et al., 2009, 2012).

Rotational profiles of jovian planets are almost symmetric with respect to the equator (Fig. 1). The asymmetry is an important parameter since it suggests whether winds on both hemispheres may be connected through the interior or are limited in depth. Uranus became the last jovian planet with data about rotational asymmetry (Karkoschka, 1998), refined by data with improved coverage (Sromovsky et al., 2012). The thin lines of Fig. 2 show the current status, excluding this work. For Jupiter, Saturn, and Uranus, root-mean-square (rms) asymmetries are 0.3%, 0.7%, and 0.5%, respectively. Neptune's data allow similar asymmetries including symmetry. Even Uranus' lonely data point at high southern latitudes shows a similar asymmetry (Fig. 2). Thus, all current data suggest that asymmetries are on the order of half a percent, so that Uranus' asymmetry might be similar even in the data gaps.

The thick curve of Fig. 2 takes the result of this work up front and contradicts these expectations. Our profile between −47° and −78° compared with Sromovsky's northern profile gives a 2% rms asymmetry, the largest asymmetry among jovian planets. If Sromovsky's extrapolation of a flat profile north of 78° latitude is roughly correct, the asymmetry near Uranus' poles is well beyond 10%.

The thick curve is based on tracking dozens of features, based on the same Voyager images that revealed only a single feature before. A revised calibration presented here allowed more accurate measurements of that feature, but discovering all the other features required new image processing methods. Thus, the critical part of this work is image calibration and processing, described in the next section. Table 1 lists key methods that were essential. Sections 3 and 4 describe rotational measurements with manual feature tracking and with a correlation method, respectively. Section 5 focuses on a feature far off the expected rotational profile. Section 6 discusses a region with an untypical rotational shear. Section 7 mentions unusual features. Section 8 lists animations available in the online version. A summary concludes this work.

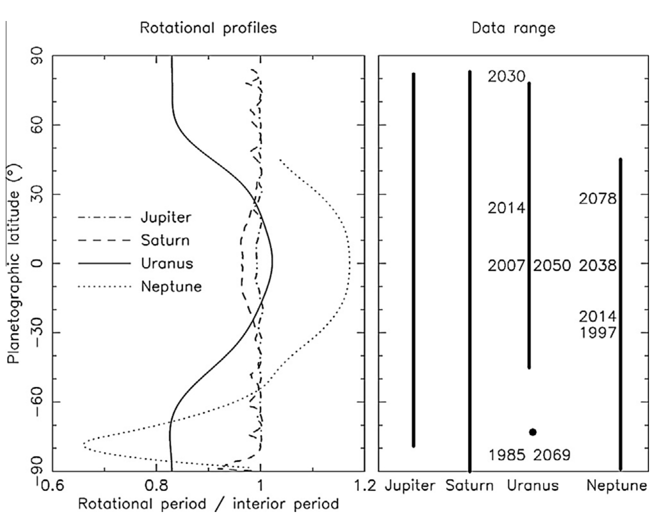


**Fig. 1.** Rotational profiles of the jovian planets normalized to interior periods (left) and the latitudinal range of data (right). Sub-solar latitudes for selected years are indicated for Uranus and Neptune. Data were taken from Limaye (1986) and Barrado-Izagirre et al. (2008) for Jupiter, from García-Melendo et al. (2011) for Saturn, from Sromovsky et al. (2012, best fit, even + odd using 1997–2011 data) for Uranus, and from Limaye and Sromovsky (1991), Sromovsky et al. (1995), and Karkoschka (2011) for Neptune.

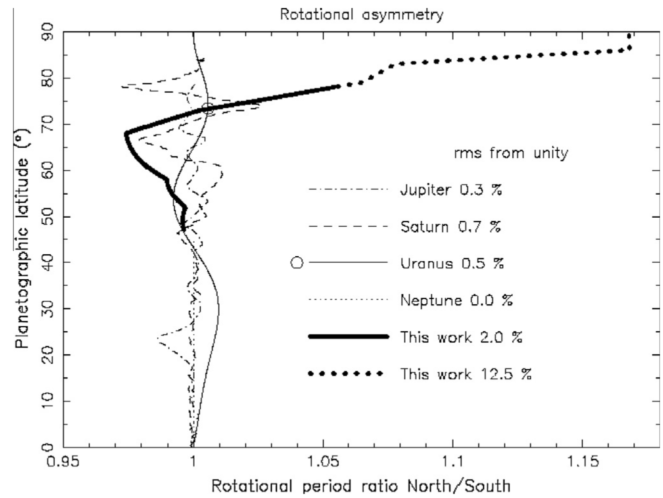


**Fig. 2.** North–south asymmetry of the rotational profiles of the jovian planets. Thin lines are from previous work (cf. Fig. 1). A data point for Uranus is indicated by a circle. The thick line is from this work. Its dotted section beyond 78° is uncertain due to the lack of data for the northern hemisphere.

**Table 1**
Key processing methods.

| Section | Method |
|---|---|
| 2.3 | Determination of detector nonlinearity curves as function of filter |
| 2.4 | Reduction of flatfield noise with the help of averaged Uranus images |
| 2.5 | High-fidelity interpolation of missing data, in particular resau marks |
| 2.11 | Elimination of large-scale detector instability |
| 2.14 | High-pass filtering to eliminate medium-scale detector instability |
| 2.16 | Averaging rotated images in order to dramatically reduce noise |
| 4.1 | Automated correlation method to track faint discrete features |

## 2. Image calibration and processing

### 2.1. Data selection

All usable images were selected since results improve with the amount of data. We excluded Uranus images taken after closest approach since they show a thin crescent with no significant detail. Images with a diameter of Uranus of less than 100 pixels were also excluded.

Images with large areas of missing data, including saturation, were excluded, also when most of the disk was outside the field of view. Long exposures with a significant smear due to imperfect tracking were excluded where the smear length was more than 7% of Uranus' radius.

These selection criteria left a total of 1600 images that are the basis for this work. Table 2 lists a summary of their parameters. The observations occurred in seven periods, called periods P1