THE ROTATION OF URANUS

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HISTORICAL REVIEW

From the start of this century until the mid-1970's the rotation rate of Uranus was reported to be *10.8 h* in a retrograde sense (see, for example, Allen, 1955), but a cursory examination of the origin of this datum reveals that little confidence should be placed in it.

Three independent techniques for measuring the rotation rate are available, each very difficult and not including the most direct method of observing the motion of features across the disc. Visual observers have reported features from time to time (see Alexander, 1965, for a full historical account), but the mean diameter of Uranus is only *3.6 arcsec* and large high contrast features are rare in the visible spectrum, if they exist at all.

The three available methods are: use of theoretical interior models together with observations of the oblateness, f, and the gravitational moment, J_2; periodic fluctuations in the brightness; spectrographic measurements of Doppler shifts (line tilts). The first report of a rotation rate close to *11 h*, based on a theoretical analysis of the planet's figure, was by Berstrand (1909; some of the early work is not easy to find and where it is only of historical importance I have relied upon Alexander's reports). At that time, there were no measurements of J_2 and no reliable data on the oblateness. The crucial early work was the spectrographic determination of 10.8 ± 0.3 *h* by Lowell and Slipher (1912). While these observers worked with exemplary care, a reanalysis of their data by Hayes and Belton (1977) shows no significant line tilts if all the data are taken together.

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Soon after the work of Lowell and Slipher came the confirmatory work of Campbell from an analysis of brightness variations. A period of *10.82 h* was announced by E. C. Pickering in 1917, but Campbell did not publish until 1936 and, in the meanwhile, work in 1918 did not support his original findings. Finally, in the early era, came the spectrographic work of Moore and Menzel (1930) whose value of *10.84 ± 0.16* was quoted most widely until a year or two ago.

The spectrographic method is extremely difficult, as is demonstrated by a wide spread of results from recent observers using much more sophisticated equipment and analytical techniques than were available to Moore and Menzel. The brightness variations give a very precise result but sometimes of doubtful significance. It appears that mutual reinforcement may have occurred based upon confidence in the superior accuracy of an alternate technique. Whatever the reason for the agreement between Lowell and Slipher, Campbell, and Moore and Menzel, there is now no longer any doubt that the *11 h* period is incorrect.

The 1981 *Astronomical Almanac* now gives - *0.65d* ? as the rotation period of Uranus. This is a period for which Robert Brown and I are responsible and it agrees with recent work on the figure of the planet. The query reflects editorial uncertainty because of some discordant measurements, to which I shall return.

One important feature of the rotation of Uranus was correctly established at an early date, namely, that the rotation axis lies close to the plane of the ecliptic with an inclination of *97°59'* (Fig. 1). Herschel noted in 1787 that the orbit of Oberon had a very high inclination. All of the rings and satellites of Uranus have similar inclinations and small precessions, facts which require that the orbits lie in the equatorial plane. This was first pointed out by Laplace in 1829, but was probably also appreciated by the Herschels. How the planet and its satellites reached this configuration is another matter (Greenberg, 1975), beyond the scope of this paper.

THE FIGURE OF URANUS

For an equilibrium rotating body the gravitational moment, J_2, and the oblateness, f, are to first order, related by (Cook, 1973):

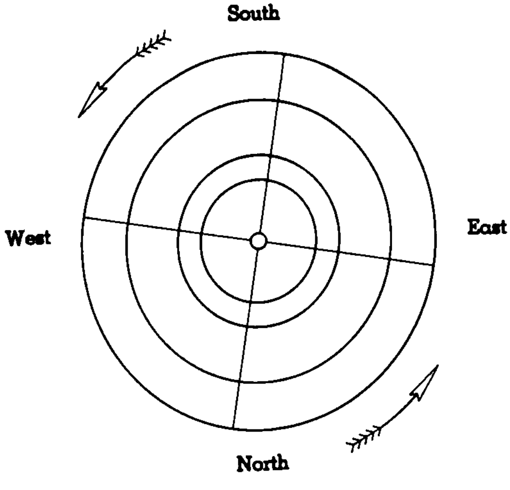
$$J_2 = 2f/3 - m/3,$$

$$m = 4\pi^2 r^3/T^2 GM,$$

where T is the rotational period, r the radius of the planet, M the mass, and G the universal gravitational constant.

Given J_2 and f, therefore, the period can be calculated. J_2 can be determined from the precession of satellite orbits, but the precession is very small and the measurement was extremely difficult prior to the discovery of the rings. Oblateness must be measured directly. It is about 2%, and its magnitude was in doubt until recent years. Another relationship between J_2, f and m can be calculated given a model of the interior of the planet (Brown and Goody, 1980; Podolak, 1976; Podolak and Cameron, 1974). Houzeau, in 1856, used speculations about the interior structure of Uranus to obtain the first estimate of the period, between *7.25 h* and *12.5 h*.

Figure 1. The appearance of Uranus and its satellites on 9 May 1981 (from the *Astronomical Almanac*, p. F62).



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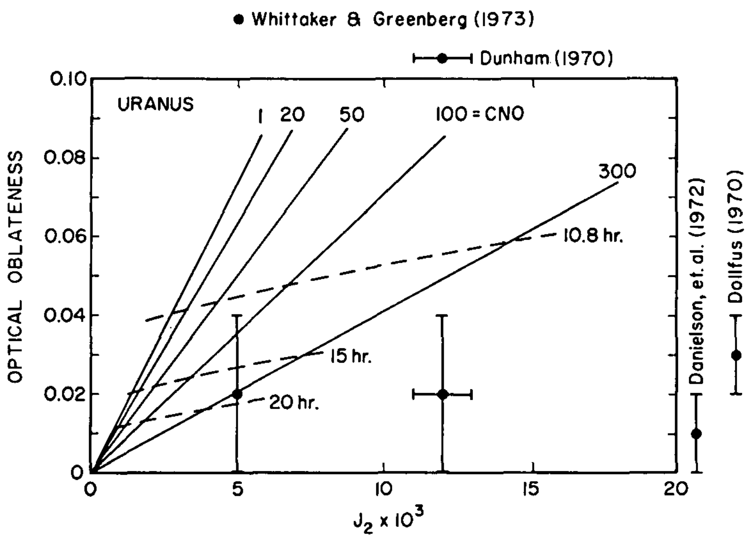
Despite a great deal of effort over the next 100 years, Houzeau's figure was not easily bettered. Figure 2 indicates the state of affairs in 1976. The two best measurements of J_2 from satellite orbit analysis are shown. The oblateness determination of Dollfuss (1970) is a summary of all ground-based work to date. That of Danielson, *et al.* (1972) is based upon measurements made by Stratoscope II. The full lines are for a range of interior models of Podolak (1976). On the basis of these data Podolak favored a period $\sim 18\ h$.

Occultation measurements on the rings of Uranus now allow very precise determinations of J_2. Nicholson, *et al.* (1978) find $J_2 = 3.43 \pm 0.02 \times 10^{-3}$, while more extensive work by Elliot, *et al.* (1980) gives $J_2 = 3.354 \pm 0.005 \times 10^{-3}$. Simultaneously, reliable data for the oblateness have become avilable. Franklin, *et al.* (1980) reanalyzed the Stratoscope II data and found $f = 0.022 \pm 0.001$. This result depends upon an understanding of the difference

Figure 2. The relationship between J_2, f and T for a range of interior models together with measurements available in 1976 (after Podolak, 1976).



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between polar and equatorial limb darkening, but the same criticism cannot be made of the work of Elliot, *et al.* (1981), which is based upon stellar occultations. Elliot, *et al.* find $f = 0.24 \pm 0.003$.

If we adopt Franklin, *et al.*'s value of f and Eliot, *et al.*'s value of J_2 we have

$$T = 16.7 \pm 0.5\ h\ .$$

BRIGHTNESS VARIATIONS

The foregoing work on the figure of Uranus seems conclusive in its indications, but it is an indirect method and confirmation from a more direct approach is desirable. Brightness fluctuations offer one possibility. A periodic change in the brightness of a planet or satellite with a period on the order of tens of hours is most likely to be associated with the appearance and disappearance of bright or dark features on the limb. Our knowledge of the rotational period of Neptune is mainly based upon such measurements although for Neptune the variations are very large, up to *2 mag* in the J-K color index, according to Belton, Wallace and Howard (1981).

The history of brightness measurements on Uranus is summarized in Table 1. Most of the references can be found in Alexander (1965); the editorial comments are my own. The table speaks for itself and shows that no convincing case for brightness variations of Uranus has been established in the published literature.

The most accurate data are those of Lockwood and Thompson (1978), working at Lowell Observatory. They made measurements with filters at and adjacent to methane bands at *6190* and *7261 Å*, because other measurements suggest that variability is at a maximum in strong methane bands. It is generally believed that clouds may occasionally form above the level of methane absorption and give rise to local brightening. Lockwood and Thompson conclude that there are no periodic variations in excess of *0.003 mag* except perhaps in the range of *23* to *25 h* where it is hard to reach a conclusion because of the difficulty of working with irregularly spaced data taken at 24-hour intervals.

Despite this difficulty, a period close to *24 h* is, in fact, claimed by a group working at the University of Texas. This work is reported in the abstract only (Smith and Slavsky, 1979): the methods are the same as those used by Slavsky and Smith (1978) for Neptune. I am indebted to David Slavsky for the following details.

Observations were made with filters in and adjacent to the *6190 Å* methane band in Texas, Chile and South Africa. Periodic variations of the brightness of Uranus of *0.006 mag* were recorded in contrast to *0.002 mag* for a comparison star. The phase for simultaneous measurements in Chile and South Africa agreed in sidereal time but not in local time, and the entire data set is consistent with a period of *23.87 h*.

Table 1. The period of Uranus from brightness variations.

Date	Observer(s)	Period	Comments
1884-85	Muller	---	No variations
1915	Waterfield	*21 d*	Probably insignificant
1916-17	Campbell	*10.82 h*	*0.15 mag* variations
1918	Campbell	---	No variations
1921-26	Wirtz	---	No variations
1926	Perenago	*10.82 h*	Poor statistics
1926	Perenago	---	No variations
1927	Slavenas	*10.82 h*	Poor statistics
1928	Stebbins/Jacobsen	---	No variations
1928	Gussow	---	No variations
1934-35	Sterne/Calder	*10.82 h*	Marginal statistics
1976	Belton	*21.48 h*	Reanalysis of Campbell's data
1977	Lockwood/Thompson	---	Less than *0.003 mag* variations except for *23-25 h* period
1980	Smith/Slavsky	*23.87 h*	Unpublished; *0.006 mag* variations

SPECTROGRAPHIC METHODS

These methods are also more direct than those based upon the planetary figure. In their simplest form the spectrograph slit is placed along the equator and a measurement made of the tilt of a spectral line.

There are many pitfalls. Line tilts are typically a few degrees. For the observations of Moore and Menzel the diameter of Uranus at the photographic plate was ~ 0.2 *mm* and the exposure time was 1-2 hours. The lateral distance between the two ends of the line averaged *5 μm* or only 0.5 grains, depending upon the characteristics of the film used.

Modern instruments give great improvements. In 1976 and 1977, Robert Brown and I (Brown and Goody, 1977; 1980) worked with the KPNO 4-meter telescope with a Cassegrain echelle to obtain both high spectral dispersion and a large image. The detector was a Kron camera having extremely fine grain combined with linearity over a wide dynamic range. Most importantly, we took steps to allow for the effect of seeing on the recorded line tilts.

The correction function is shown in Fig. 3. The recorded line tilt decreases as the seeing disc increases in size. For *s arcsec* the recorded line tilt must be increased in the ratio $G(0)/G(s)$ before interpretation as a Doppler shift. For a seeing disc of *2 arcsec* this ratio is about 1.6. For the long exposures of Moore and Menzel the correction factor (which they did not apply) must be at least this great, although this only serves to increase the discrepancy between their value and all modern determinations.

Seeing can be measured from scans across the spectrum in continuum regions, but use of this result requires that seeing and guiding errors be isotropic. To eliminate the typical bias between errors in RA and Dec we employed automatic guidance on all occasions.

In 1976 we measured the tilts of 23 lines and obtained a rotational period of $15.57 \pm 0.80\ h$, while in 1977 we measured more than 600 lines for a period of $16.26 \pm 0.34\ h$. Both data sets are consistent with

$$T = 16.16 \pm 0.33\ h\ .$$

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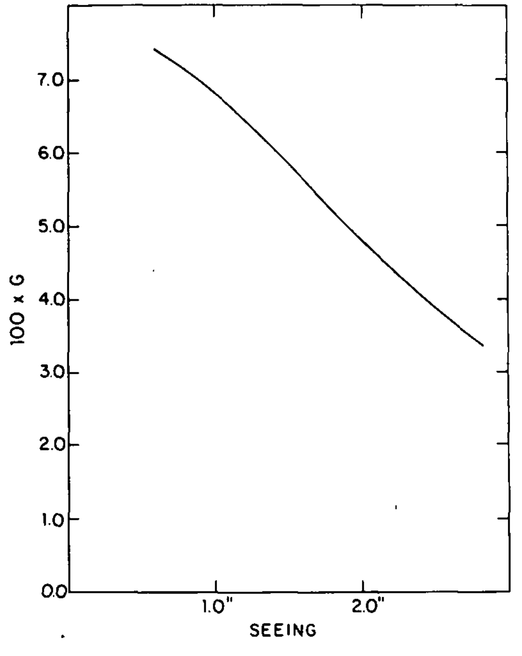
We were also able to confirm that the rotation axis corresponded with the pole of the satellite orbits.

The work was only one of a number of simultaneous attempts to improve spectrographic determinations of Uranus' period. Trauger, Roessler and Münch (1978) used a whole-disc approach which avoids seeing corrections. It requires a knowledge of incoherent scattering processes, however, about which we cannot be confident. Trafton (1977) employed an ingenious variant of the normal spectrographic technique which is, however, subject to large errors. I shall therefore restrict my discussion to the work of Münch and Hippelein (1980) and Hayes and Belton (1977).

Figure 3. Seeing correction to line tilt based on measurements of synthetic spectra. For perfect seeing $G(0)$ is 7.65×10^{-2} (after Brown and Goody, 1977).



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The former obtain a period of $15.0^{+4.0}_{-2.6}$ *h*, consistent with our work, and they provided a quasi-analytical basis for the seeing correction. Hayes and Belton obtained 24 ± 3 *h*, consistent with the work of Smith and Slavsky, but irreconcilable with our determination.

Hayes and Belton used essentially the same equipment as we did and employed a similar method of analysis. It is difficult to avoid the conclusion that one piece of work or the other contains numerical errors. With elaborate numerical algorithms such errors are regrettably easy to make and hard to detect. In a subsequent paper, Belton, Wallace, Hayes and Price (1980) mention "two serious sources of error" in the earlier work but state that their results for Uranus are unaffected.

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The weighted mean of our data and that obtained from the planetary figure are

$T = 16.31 \pm 0.27$ *h*,

The values of J_2 and f are now firmly established. For the rotational period to be wrong the equilibrium theory of the figure must be inapplicable. It works very well for all other planets for which data exist, except for the Moon.

The work of Slavsky and Smith cannot be evaluated until it is published and the only established discrepancy with the above result is, therefore, the work of Hayes and Belton. Unfortunately, it will be a long time before the spectrographic work can be repeated successfully, even assuming that investigators will exist with the desire to do so. The aspect of the planet is becoming increasingly unfavorable. In 1985 the North Pole will point directly toward the Sun and seven or eight more years must elapse before there is a substantial component of the rotation vector orthogonal to the line of sight.

The possibility of detecting the motion of features across the disc remains. Nisenson, *et al.* (1981) have reported on the use of speckle imaging techniques to obtain images of Titan with a resolution of 0.29 *arcsec*. With this equipment Uranus can be imaged in the *6190 Å* methane band and with more suitable image intensifiers, also in the *7261 Å* band. If large cloud systems appear above the level of methane absorption it may be possible to detect them.

Finally, the Voyager II flyby in January 1986 may show features on the disc, in which case the controversy over the Uranus rotation period should be finally resolved.

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