

THE SEVEN IDENTIFIED OBSERVATIONS OF URANUS MADE BY JOHN FLAMSTEED USING HIS MURAL ARC

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Introduction

During the nineteenth century, allegations and verifications of Flamsteed's observations of Uranus were published by M. Burkhardt¹, F. Baily^{2,3}, F. Baily³, F. W. A. Argelander⁴, and C. H. F. Peters⁵ (see Table I). D. Rawlins⁶ published a verification, in the 20th century, of a "long lost observation" which had been published by C. H. F. Peters⁵ near the end of the 19th century. There was some confusion in the early years of the nineteenth century about some of the observations (see p. 162 of ref. 3). These investigations were probably prompted by the search for useful pre-discovery observations to improve the orbital elements of the planet.

Of course, nineteenth century quantitative knowledge of the astronomical constants, the astronomical reference frame, and the heliocentric motions of the planets was in the formative stage. Today, at the end of the twentieth century, the most accurate values of these quantities are available^{7,8}. Also, the most accurate compilation of the mean places and proper motions of stars on the FK5 system is now available⁹.

With these new data, it is possible to study the seven original handwritten sets of observations, available from microfilms, by methods which were not available to the nineteenth century analysts. On the nights when Flamsteed made the seven identified observations of Uranus, with the Mural Arc, he also observed at least three stars and as many as ten. It is possible to predict the apparent right ascensions of the stars with an accuracy of about 0.1 second and the declinations with an accuracy of about 1 arcsec¹⁰. A differential method was devised to extrapolate the apparent right ascension of an observed star to that of Uranus utilizing the differences of the clock readings. It is necessary to take into account the daily clock rate, which can be estimated from Flamsteed's "revolutio", or from successive observed wire-transits of the same star, and the conversion to the sidereal interval of the mean time difference. For extrapolation of the declinations, the differences of the Mural Arc readings were utilized, taking into account any significant differential mean refraction.

The analyses

Means of the extrapolated values of the observed apparent places of Uranus for each night were calculated. Predictions of the apparent places of Uranus for Universal Times estimated by the author from the observations were provided for all seven cases by E. M. Standish of the Jet Propulsion Laboratory using the DE403/LE403 Export Ephemeris. See Table II for a summary and comparison.

Commentary

Uranus was in the constellation Taurus in the years 1689–1697, in Gemini 1697–1703, in Cancer 1703–1708, and in Leo 1708–1716. If Flamsteed made any observations in the appropriate month and the appropriate constellation,

TABLE I

Alleged and/or verified observations of Uranus

Case	Catalogue Entries	Date Julian Calendar	Date Gregorian Calendar	J.F. Clock Reading Wire Transit <i>h, m, s</i>	J.F. Mural Arc <i>°', ''</i>	Reference No. Allegation/Verification
1.	B/F 492	12/13/1690 Sat.	12/23/1690	9 41 49	31 54 57 S	2
2.	F 271	03/22/1712 Sat.	04/02/1712	9 35 19	40 40 30 S	1,3
3.	B/F 1647 F 289	12/04/1714 Sat.	12/15/1714	18 04 32	47 31 20 S	2,4,5,6
4.	F 286	02/22/1715 Tue.	03/05/1715	12 27 01	46 47 50 S	1,3
5.	F 286	02/23/1715 Wed.	03/06/1715	12 22 59	46 47 00 S	1,3
6.	F 286	02/28/1715 Mon.	03/11/1715	12 01 42	46 41 40 S	1,3
7.	F 283	04/18/1715 Mon.	04/29/1715	08 50 44	46 00 10 S	1,3

The source for Case 1. was RGO1/4; for the rest, the source was RGO1/8, Royal Greenwich Observatory Archives, Cambridge University Library.

B/F: Baily/Flamsteed edited British Catalogue².

F: Stars observed by Flamsteed but not inserted in the *British Catalogue*³.

S: Zenith Distance, South.

Dates are given in Flamsteed's notation.

there was some likelihood that Uranus would be observed. The opposition visual magnitude of Uranus is about $+5.3$; wire transits using the Mural Arc could be observed with little difficulty.

The possibility of observation of a bright minor planet was investigated. The opposition visual magnitudes of Vesta, Ceres, Pallas, and Juno are $+5.8$, $+6.5$, $+7.6$, and $+8.6$, respectively. It has been stated that Flamsteed observed stars as faint as $+8$ visual magnitude. This is compatible with the aperture of the telescope of the Mural Arc. In order to test whether any of the four minor planets were observed, an approximate value of the geocentric longitude of each of the four at the time of each observation of Uranus can be estimated. If any of the longitudes differ greatly from that of Uranus, that minor planet was not observed by Flamsteed.

To calculate the approximate heliocentric longitudes of the four minor planets at the times of the Uranus observations, it is necessary to have available osculating orbital elements. It would be preferable to have such elements for the early 1700's but, of course, these minor planets were discovered in the early 1800's. Gauss's elements are the earliest available¹¹ and they would have less effect of perturbations than any later set. The orbital inclinations of Vesta, Ceres, Pallas, and Juno are about 7° , 11° , 35° , and 13° , respectively. The assumption was made that a minor planet's heliocentric longitude was approximately equal to the sum of the longitude of the ascending node, the argument of perihelion, and the true anomaly at the time of an observation of Uranus. These longitudes may have an error of a few degrees. The heliocentric longitude of the Earth and the geocentric longitude of Uranus were calculated using commercially available software. A spreadsheet program was developed to calculate the eccentric anomaly, the true anomaly, and the radius vector. The approximate geocentric longitudes of the four minor planets at the times of each of the

TABLE II

Comparisons of observations with predictions of JPL DE403/LE403

Case No.	Number of Stars	Mean Extrapolated RA <i>h, m, s, SD**</i>	JPL RA* DE403/LE403 <i>h, m, s</i>	Mean Extrapolated DEC <i>°, ', ", SD**</i>	JPL DEC* DE403/LE403 <i>°, ', "</i>
1	10	03 43 17 ± 1 ^s .3	03 43 17	19 35 17 ± 5''	19 35 12
2	5	10 22 39 ± 1 ^s .8	10 22 35	11 00 59 ± 6''	11 00 53
3	3	11 29 01 ± 2 ^s .3	11 29 01	04 11 09 ± 8''	04 11 17
4	3	11 22 40 ± 2 ^s .3	11 22 40	04 54 32 ± 8''	04 54 37
5	3	11 22 32 ± 2 ^s .3	11 22 31	04 55 27 ± 8''	04 55 38
6	4	11 21 43 ± 2 ^s .0	11 21 42	05 00 43 ± 7''	05 00 46
7	3	11 15 02 ± 2 ^s .3	11 15 03	05 41 57 ± 8''	05 42 00

* Correction for geocentric parallax is negligible.

** The extrapolated RA's are linear functions of the clock readings of each star observation, the clock reading of the Uranus observation, and the calculated RA of the star. The extrapolated DEC's are linear functions of the arc reading of each star observation, the arc reading of the Uranus observation, and the calculated DEC of the star. The standard deviations (SD) of the mean Extrapolated RA's and DEC's are calculated by the theory of least squares for functions of independent variables.

Case 1: Used 13, 14, 25, 27, 32, 33, 36, 37, 42, 44 Tau for calculation.

Case 2: Used 47, 8, 51, 0, 59, 64, 79 Vir for calculation. J.F. noted ρ for this observation. Uranus was near ρ Leo.

Case 3: Used 5, β Vir; 15, η Vir; 29, γ Vir for calculation. Argelander calculated RA 11 29 02, DEC 04 11 07 for Uranus. Peters calculated RA 11 29 03, DEC 04 11 06 for Uranus. Rawlins calculated RA 11 29 01, DEC 04 11 24 for Uranus.

Case 4: Used 58 Leo, 65 Leo, 7 Vir for calculation. Burkhardt calculated RA 11 22 41, DEC 04 54 23 for Uranus.

Case 5: Used 58 Leo, 65 Leo, 7 Vir for calculation. Flamsteed noted :: for the clock time of wire crossing for Uranus.

Case 6: Used 58 Leo, 65 Leo, 80 Leo, 7 Vir for calculation. Burkhardt calculated RA 11 21 43, DEC 05 00 39 for Uranus.

Case 7: Used 77, σ Leo; 3, ν Vir; 17 Vir for calculation.

seven observations of Uranus were estimated from a polar coordinate plot of the above calculated data.

The smallest difference in geocentric longitude between Uranus and a minor planet for all 28 longitude comparisons was about 35° and a number of differences were nearly 180°. Thus a possible observation of one of the four minor planets was ruled out in all cases.

It remains to speculate on the reasons why Flamsteed didn't recognize that the object was not a star. There are only two ways that a solar-system object could have been detected; first, by showing an appreciable disc in the field of view of a telescope and second, by its angular motion with respect to the nearby stars.

During the second of his four reviews of the heavens visible at his site, William Herschel discovered in Gemini, during 1781 March, a previously unknown object which was later identified as Uranus¹². He perceived that it appeared "visibly larger than the rest" of the stars in the field of view. The apparent angular diameter of Uranus is about four arcsec. The telescope he was using was one of his better seven-foot Newtonian reflectors, with a speculum metal mirror of diameter about 6.2 inches. Presumably, the figure of the mirror was at least within one quarter of a wavelength of visual light of a true paraboloid. Applying Dawes empirical criterion to this telescope, he should have been able to resolve a double star of angular separation about 0.7 arcsec. The objective of Flamsteed's Mural Arc telescope was a simple lens approximately two inches in diameter and ideally it would be capable of resolving a double star of angular separation about 2 arcsec. However, the spherical and chromatic aberrations

TABLE III
Mural Arc Readings

Case	Uranus ° ' "	58 Leo ° ' "	65 Leo ° ' "	7 Vir ° ' "
4	46 47 50	46 34 20	48 13 20	46 28 00
5	46 47 00	46 34 20	48 13 20	46 28 00
6	46 41 40	46 34 15	48 13 15	46 28 05

would degrade the resolving power further, so that the image of Uranus would not be greatly different from that of the stars. We can forgive Flamsteed for not recognizing Uranus directly.

The angular motion of Uranus in even one day was sufficient to be detected by Flamsteed's Mural Arc. Unfortunately, cases 1 to 4 were observed on single nights of different years. But cases 4, 5, 6 were observed within one week. In Table III, Mural Arc readings are tabulated for the three cases for the object later identified as Uranus and also for the three stars observed in the vicinity.

Uranus was near opposition at these times (elongation 174° to 179°) and was executing the usual looping geocentric motion on the celestial sphere. It is obvious that the unknown object observed is moving, while the arc readings for the stars show fixed positions except for reading errors. Flamsteed did not often review a night's observations soon after they were made. Most of the reductions were made many years after the observations! Uranus was present in the field of stars observed on a number of other nights of Mural Arc observations, but it was not observed. If Flamsteed had detected that the observed object was not a star and was moving with respect to the stars, geocentric positions of Uranus of moderate accuracy would have become available at least 66 years before Herschel's observation. This would have been of great assistance to the nineteenth century astronomer in developing improved orbital elements of the planet.

The comparison in Table II may be viewed in two ways. First, it may be viewed as the most accurate verification of the identification of the observations as those of Uranus. Second, it may be viewed as a confirmation that the predictions of DE403/LE403 have displayed very little bias errors over a time interval of about 300 years.

References

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