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The Diameter of Neptune

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Fourteen meridian circle observations made before and after the occultation of ZC 2232 by Neptune on 7 April 1968 and observations of the occultation from Japan, New Zealand, and Australia have been used to determine corrections to the ephemeris of the relative positions of the star and Neptune, of $+0^{s}.260\pm0^{s}.001$ in right ascension and $-0''.46\pm0''.07$ in declination, and a new semidiameter of Neptune of $33''.9\pm1''.8$ at unit distance.

On the 7th of April 1968, Neptune occulted a star as bright as itself, Zodiacal Catalog 2232 (BD −17°4388, SAO 159409), and it was hoped that observations of this rare event (visible from Australia, New Zealand, and Japan) could be used to determine the diameter of Neptune and a correction to its ephemeris. Since Neptune was deviating from its ephemeris enough to change markedly the circumstances of the occultation, it was questionable as to whether or not the occultation observations could be used to determine uniquely the diameter of Neptune. Therefore, the U. S. Naval Observatory's Six-Inch Transit Circle Division was asked to make differential measures of the distance in right ascension (α) and declination (δ) between Neptune and ZC 2232 before and after the occultation. Fortunately, the results of photographic measures made at Mt. Stromlo and Yale University during the period when the planet and the star were too close to be measured by the transit circle were also available.

The transit circle observations, listed in Table I, are differential measurements made by the six-inch transit circle at the time of meridian passage on each date of observation. These were supplied to us by F. S. Gauss. The columns headed $\Delta\alpha$ and $\Delta\delta$ are in the sense of star minus Neptune. Times here and throughout this paper are Universal Time.

The column $R\Delta\delta$ is the differential refraction and has been added to the declination for the meridian circle observations.

Photographic observations were made at the Yale University Observatory at Bethany, Connecticut, with a 40-inch reflector (Dunham 1968), and at Mt. Stromlo Observatory in Australia with a 26-inch refractor (1969, *IAU Circ.* 2086; Miller 1968), and are also listed in Table I.

The observed separations have been compared with the predicted separations ($O-C$'s) to derive corrections to the ephemeris of star minus Neptune. The ephemeris

TABLE I. Differential observations.

Date	Time	$\Delta\alpha$ (observed)	p.e.	$\Delta\alpha$ (computed)	$O-C$	$\Delta\delta$ (observed)	p.e.	$R\Delta\delta$	$\Delta\delta$ (computed)	$O-C$
Meridian Circle										
18 Feb	$11^{h}02^{m}$	$-97^{s}.210$	$\pm0^{s}.006$	$-97^{s}.527$	$+0^{s}.317$	$+482''.31$	$\pm0''.16$	$0''.47$	$+483''.01$	$-0''.70$
26 Feb	10 26	−102.918	0.005	−103.199	0.281	+473.86	0.17	0.46	+474.33	−0.47
27 Feb	10 31	−103.063	0.013	−103.063	0.221	+470.74	0.20	0.44	+471.15	−0.41
4 March	09 49	−100.660	0.006	−100.919	0.259	+442.19	0.25	0.42	+442.66	−0.43
7 March	09 42	−97.622	0.008	−97.904	0.282	+421.44	0.13	0.40	+422.34	−0.90
8 March	09 33	−96.291	0.013	−96.638	0.347	+414.75	0.29	0.40	+414.74	+0.01
14 March	09 09	−86.003	0.007	−86.286	0.283	+359.88	0.11	0.36	+360.21	−0.33
29 March	08 18	−40.727	0.007	−41.012	0.285	+161.08	0.42	0.15	+162.32	−1.24
2 April	08 02	+24.449	0.007	−24.657	0.208	+95.14	0.11	0.10	+96.26	−1.12
12 April	07 22	+23.142	0.009	+22.957	0.185	−89.18	0.21	0.08	+89.03	−0.15
13 April	07 18	+28.495	0.020	+28.194	0.301	−110.49	0.18	0.10	−108.94	−1.55
16 April	07 06	+44.587	0.007	+44.366	0.221	−171.69	0.41	0.16	−170.03	−1.66
17 April	07 02	+50.125	0.008	+49.903	0.222	−190.53	0.29	0.17	−190.82	+0.29
26 April	06 26	+102.869	0.013	+102.654	0.215	−386.53	0.21	0.36	−385.85	−0.67
Yale Observatory										
6 April	$8^{h}37^{m}00^{s}.0$	$-6^{s}.270$	...*	$-6^{s}.532$	$+0^{s}.262$	$+24''.09$	...*		$+24''.72$	$-0''.63$
7 April	8 39 30.0	−1.524	$\pm0^{s}.007$	−1.783	0.259	+5.55	$\pm0''.03$		+6.20	−0.65
8 April	6 05 22.9	+2.780	0.003	+2.517	0.263	−11.08	0.01		−10.53	−0.55
Mt. Stromlo										
5 April	$13^{h}42^{m}35^{s}.1$	$-9^{s}.916$	$\pm0^{s}.004$	$-10^{s}.223$	$+0^{s}.307$	$+37''.94$	$\pm0''.07$		$+38''.73$	$-0''.79$
6 April	15 10 14.3	−5.004	0.003	−5.258	0.254	+18.81	0.05		+19.35	−0.54
7 April	17 19 20.0	+0.182	0.006	−0.060	0.242	−1.14	0.15		−0.63	−0.51
8 April	14 46 08.4	+4.533	0.001	+4.271	0.262	−18.18	0.09		−17.46	−0.72

* Single observation.

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TABLE II. Observations of the occultation; preliminary semidiameter estimates.

A. Photoelectric observations

Luminosity	Tokyo Astronomical Observatory (*IAU Circ.* 2068) Dodaria	Tokyo Astronomical Observatory (*IAU Circ.* 2068) Okayama	Mt. John University Observatory (Guinan 1968)	Mt. Stromlo (*IAU Circ.* 2067) 127-cm	Mt. Stromlo 76-cm	Siding Spring (*IAU Circ.* 2067) 41-cm	Siding Spring 61-cm
(disappearance)							
1.00 (1st contact)	$15^h56^m16^s$	$15^h56^m45^s$	$15^h54^m25^s \pm 10^s$	$15^h56^m15^s$	$15^h56^m20^s$	$15^h56^m23^s$	
0.75	15 56 20	15 56 48					
0.50 (half-power)	15 56 25	15 56 54	15 54 56 ± 1	15 56 29	15 56 30	15 56 41	$15^h56^m30^s.5$
0.25	15 56 30	15 57 01					
0.00	15 57 00	15 57 27					
(reappearance)							
0.00	16 40 04	16 41 27					
0.25	16 41 21	16 41 46					
0.50 (half-power)	16 41 31	16 41 51	16 34 39 ± 1	16 36 46	16 36 47	16 37 17	16 37 01.5
0.75	16 41 35	16 41 59					
1.00 (last contact)	16 41 39	16 42 06	16 35 05 ± 5	16 36 58	16 37 00	16 37 36	
Preliminary Semidiameter: (from half-power point)	$1''.20$	$1''.20$	$1''.20$	$1''.21$		$1''.21$	

Observatory	Position λ	Position φ	Position h	Description
Dodaria	139°11′36″.791*E*	+36°00′10″.384	879 m	91-cm reflector
Okayama	133 35 46.607*E*	+34 34 22.850	365 m	91-cm reflector
Mt. John	$11^h21^m51^s.533$*E*	−43 59 15.0	(not reported)	10-inch refractor, 16-inch reflector. E. F. Guinan and S. Shaw, observers
Mt. Stromlo	211°59′39″.8*W*	−31 19 16.0	768 m	127-cm reflector K. Freeman, observer; 76-cm reflector G. Lyngå, observer
Siding Spring	210 19 00.0*W*	−35 15 00.0	1164 m	41-cm reflector N. Stores, observer; 61-cm reflector K. Serkowski, observer

B. Visual Observations

	Townsville Moonwatch Group (1968) Neil D. Butterworth	Townsville Moonwatch Group (1968) Alistair MacDonald	Carter Observatory (1968) T. L. Thomsen	Carter Observatory (1968) W. J. H. Fisher	Carter Observatory (1968) A. C. Gilmore
Disappearance					
Fading noticed	$15^h56^m30^s.7$		$15^h54^m45^s.6$		
Star not seen			15 55 04.7		
Reappearance					
Change observed				$16^h34^m09^s$	$16^h33^m23^s$
First reappeared		$16^h38^m02^s.4$	16 34 37.5	16 34 16	
Full brightness	16 38 02.4		16 34 53.3		
Preliminary semidiameter	$1''.19$			$1''.22$	

	Position λ	Position φ	Position h	
Townsville Moonwatch	213.2558*W*	−19.2575	20 m	6 in F9 Newtonian, N. Butterworth; 10 in F5 Newtonian, A. MacDonald
Carter Observatory				
Thomsen	$11^h39^m03^s.69$	−41°17′03″.9	129 m	9 in refractor
Fisher and Gilmore	11 39 03.67	−41 17 04.2	129	16 in Cass. Gilmore observed with the 6-inch guide telescope

of Neptune is from the Astronomical Papers of the American Ephemeris (Eckert, Brouwer, Clemence 1951), while the position of the star is that given in Robertson's Catalog of Zodiacal Stars (Robertson 1940), as reduced to the FK4 system by applications of corrections given by Martin (1965). The published ephemeris of Neptune is not a good representation of its orbit because of an incorrect assumed mass for Pluto. This is explained in further detail by Duncombe, Klepczynski, and Seidelmann (1968). ZC 2232 has been

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included in the Southern Reference Star Program (Gauss 1968), and an improved position should be available in a few years.

The predicted differential positions in the sense star minus Neptune for the meridian and photographic observations, along with the $O-C$'s, are listed in Table I.

From the meridian circle observations, corrections were derived to the ephemeris of star minus Neptune of $+0\overset{s}{.}258$ with a probable error of $\pm0\overset{s}{.}008$ in right ascension and $-0\overset{''}{.}60\pm0\overset{''}{.}13$ in declination. These were applied to the predictions at the time of observation of the occultation events to find the true relative position of the star and Neptune at those moments. From the photographic observations, the corrections are to right ascension, $+0\overset{s}{.}261\pm0\overset{s}{.}006$, and to declination, $-0\overset{''}{.}57\pm0\overset{''}{.}08$. These were used for confirmation of the meridian circle observations, and not as independent data, since much of the material arrived after completion of our solution.

Considerable care was taken to investigate and eliminate sources of systematic error in the observations. F. S. Gauss and H. E. Crull of the Six-Inch Transit Circle Division looked into the problem of screw error and differential refraction for the transit circle measures. Differential refraction was large enough to be quite significant and its effect was removed. The screw error for right ascension had been investigated out to the distance required and was found to be negligible. The screw error for declination had not been investigated to the distance required by the observations, but extrapolations of known errors and comparison with the α scale showed it too was likely to be negligible. Since the six-inch transit circle measurements were differential, the other instrumental corrections were negligible.

The problem of differential color refraction between the two objects was also considered. The star is a K0 object; the planet reflects light from a G2 star. Investigation showed that for a photovisual detector, the effective wavelength change between the two objects is less than 5 Å (Seares and Joyner 1943). Both the Mt. Stromlo and Yale University plates were made with a series of filters designed to limit the entering light to a narrow band, so that differential color refraction is eliminated.

There were a number of observations of the occultation, both visual and photoelectric. The locations and timings of the observers are listed in Table II, along with the semidiameter that each gives for Neptune for the time of the occultation.

The mean semidiameter was then $1\overset{''}{.}20\pm0\overset{''}{.}11$ (or $35\overset{''}{.}36\pm3\overset{''}{.}25$ at unit distance), using the meridian circle differential observations to locate the center of Neptune. This was used as the first approximation in a least-squares solution, with the equation of the form

$$x^2+y^2-r_0^2=2(x\delta x+y\delta y+r_0\delta r),$$

where r_0 is the semidiameter of Neptune and x and y are $\Delta\alpha\cos\delta$ and $\Delta\delta$, respectively. ($\Delta\alpha$ and $\Delta\delta$ represent the position of the star with respect to the center of Neptune at the observed times of immersion and emersion.) This new solution gave corrections to the adopted meridian circle solution of $+0\overset{s}{.}002$ in α, $+0\overset{''}{.}14$ in δ and $-0\overset{''}{.}05$ to the radius, so that the final values are then: $\Delta\alpha=+0\overset{s}{.}260\pm0\overset{s}{.}001$, $\Delta\delta=-0\overset{''}{.}46\pm0\overset{''}{.}07$, and the semidiameter $=1\overset{''}{.}15\pm0\overset{''}{.}06$ (or $33\overset{''}{.}89\pm1\overset{''}{.}77$ at unit distance) for the half-power point.

The value for the semidiameter of Neptune of $1\overset{''}{.}24$, given in the *American Ephemeris* for the time of occultation, was based on a determination by E. E. Barnard. The measurements were made with a micrometer on the 36″ refractor at Lick Observatory from November 1894 to March 1895 (Barnard 1897). His observations gave a value of the semidiameter at unit distance of $35\overset{''}{.}54\pm0\overset{''}{.}30$. The discrepancy between these two sets of observations may possibly be explained by the fact that no correction for irradiation has been applied to Barnard's observations.

The results of the occultation observations presented here are in reasonably good agreement with preliminary and completely independent results recently announced by Taylor (1968), who also obtained a radius of $1\overset{''}{.}15$ for the half-power point. It is noted that both meridian circle and photographic observations imply a larger negative declination correction (and consequent larger radius). However, no known source of systematic error was left unchecked; and considering the size of the probable errors, the discrepancy is not at all beyond the realm of possible coincidence.

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