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A History of the Determination of Pluto's Mass

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Lowell's value for the mass of Planet X was about seven times that of the Earth. Postdiscovery determinations of the mass of Pluto from analysis of the observed motions of Uranus and Neptune reduced this value to about one Earth mass. More extended analyses in the past 10 years have lowered this value to about one-tenth of an Earth mass. The mass so derived, however, fails to agree by a factor of 50 with that determined from the motion of the newly discovered satellite Charon. The discrepancy may arise from unmodeled effects in the motions of the outer planets.

Modeling the motions of the observed objects in the solar system has long engaged the attention and effort of scientists. The representation of these motions by empirical methods gave way in the 16th century to dynamical methods based on the Universal Law of Gravitation and Newtonian mechanics. The tremendous achievements of LeVerrier and Newcomb in developing general perturbation theories of the motion of the principal planets have long stood the test of time. More recently, with the introduction of high-speed computing equipment, efforts in the representation of motions within the solar system have turned to numerical theories with extensive projects being carried out in this country at the Jet Propulsion Laboratory, the Massachusetts Institute of Technology, and the U.S. Naval Observatory.

Determination of the presence and location of Neptune from the observations of Uranus impressed firmly on the minds of scientists the power of celestial mechanics. Thus it was not long after the discovery of Neptune in 1846 that predictions were being made that yet another planet lurked in the vastness of space beyond Neptune. Three dynamical methods exist for the determination of the mass of a planet:

(1) measurement of its effect on the secular change of the elements of a perturbed planet or spacecraft;

(2) measurement of the periodic effects induced in the orbital motion of a perturbed planet or spacecraft; and

(3) measurement of the semimajor axis of the orbit of a satellite of the planet.

The first two methods require observation of the perturbed planets over an extended period of time for a reliable determination of the mass of the perturbing body. The third method yields results on a much shorter time span; that is, by observations over several orbital periods of the satellite. Table I lists representative values of the mass of the unnamed planet (later Pluto) commencing shortly after the discovery of Neptune. These estimates, with the exception of the last two, rest entirely on analysis of the observations of Uranus and Neptune.

The interesting, and sometimes astounding, attempts to predict the presence and

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TABLE I

MASS DETERMINATIONS

Date	Investigator	Observations	Mass in terms of the Earth
1848	J. Babinet	Neptune	12
1899	H. Lau	Uranus	9
1908	W. Pickering	Uranus	2
1909	B. Gaillot	Uranus, Neptune	5
1915	P. Lowell	Uranus, Neptune	6.6
1928	W. Pickering	Uranus, Neptune	0.75
1930	J. Jackson	Neptune	1.0
1931	Nicholson and Mayall	Neptune	0.94
1931	E. Brown	Uranus	0.5
1940	V. Kourganoff	Uranus	1.0
1942	L. Wylie	Neptune	0.91
1951	Eckert, Brouwer, and Clemence	Neptune	1.0
1955	Brouwer	Uranus, Neptune	0.82
1968	Duncombe, Klepczynski, and Seidelmann	Neptune	0.18
1971	Seidelmann, Klepczynski, Duncombe, and Jackson	Neptune	0.11
1971	Ash, Shapiro, and Smith	Uranus, Neptune	0.08
1976	Cruikshank, Pilcher, and Morrison	Albedo	0.004
1978	Christy and Harrington	Satellite	0.002

size of additional planets in the solar system are chronicled in a very thorough and entertaining way by Hoyt (1980). The early analyses of Babinet in 1848 (Grosser, 1976) and Lau (1900) grossly overestimated the mass of the unknown planet. The analysis, commenced about 1905 by Percival Lowell, and culminating in his memoir of 1913 (Lowell, 1915), represents the most thorough application of dynamical principles to the observations of Uranus and Neptune up to that time. His estimate of the mass of the unknown planet "X" as 6.6 times that of the Earth is matched only by the value of Gaillot (1909). W. H. Pickering (1919), commencing his analysis in 1908, but using less precise graphical methods, derived a mass twice that of the Earth for his unknown planet "O" from observations of Uranus and Neptune. By 1928, Pickering (1928), had reduced his estimate of the mass of planet "O" to three-fourths that of the Earth, but he had also succeeded in expanding the outer solar system with additional planets P, Q, R, S, T, and U (Hoyt, 1976). In the 25 years following the discovery of Pluto by Clyde Tombaugh, analyses by Jackson (1930), Nicholson and Mayall (1931), Wylie (1942), and Kourganoff (1940) of the observations of Uranus and Neptune yielded values for the mass of Pluto approximately equal to 1 Earth mass. Exceptions are the determination by E. W. Brown (1930), which gave a value of half an Earth mass, and the estimates of Bower (1931) and Crommelin (1930) who proposed values of $\frac{1}{10}$th of an Earth mass based on brightness and size. The extensive integration of the orbits of the five outer planets by Eckert *et al.* (1951) incorporated a mass of Pluto equivalent to 1 Earth mass, and they pointed out that this value was required to

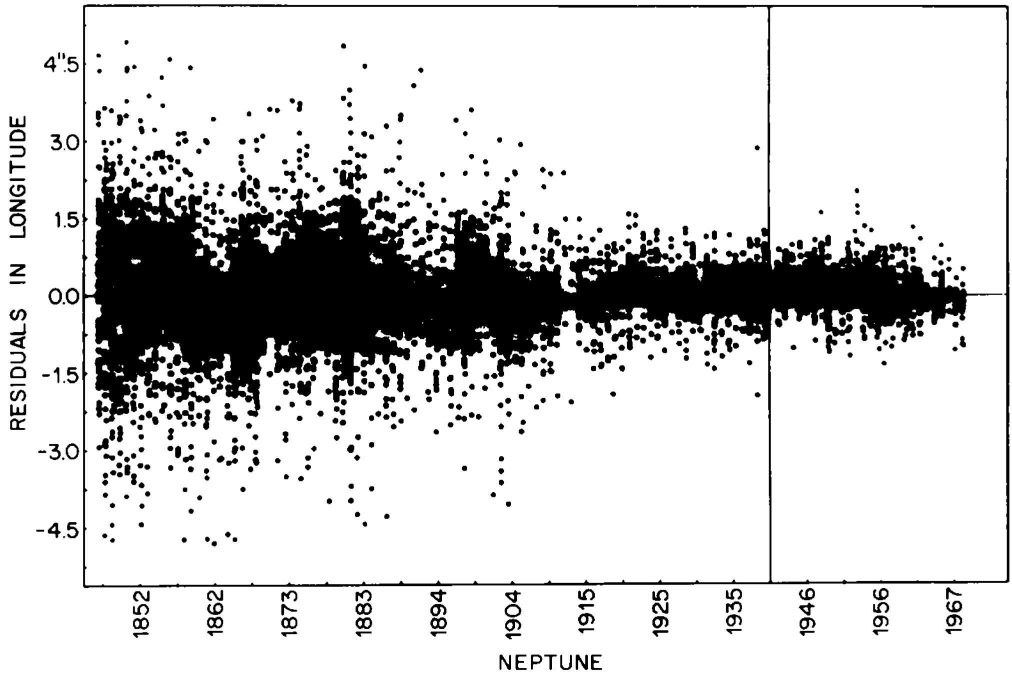

FIG. 1. O − C, longitude of Neptune, 1846–1968. Reprinted, with permission, from Seidelmann *et al.*, 1971.

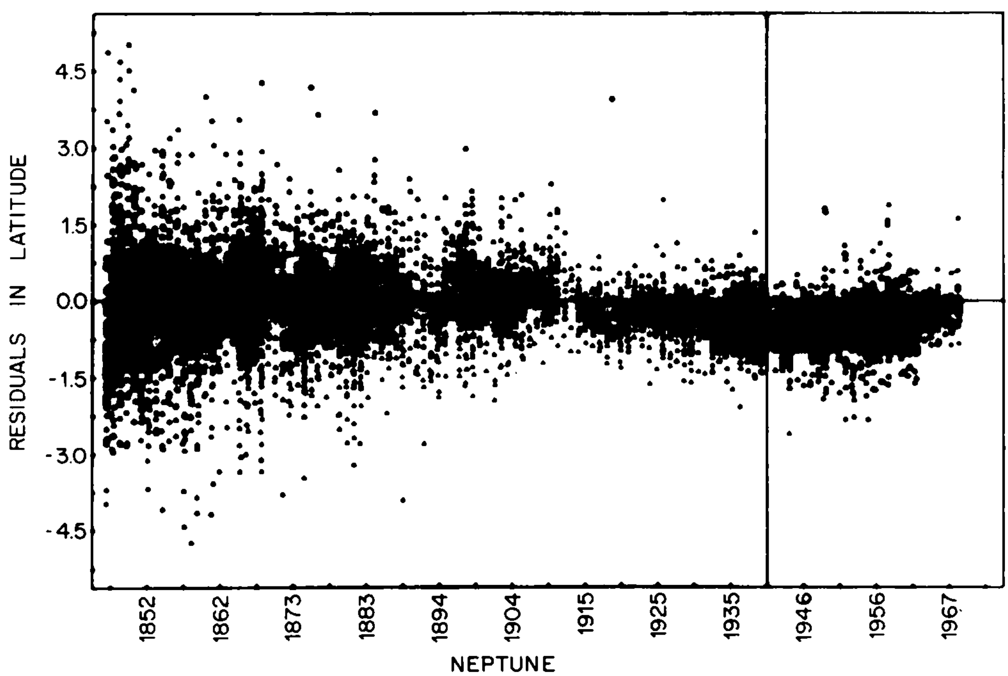

FIG. 2. O − C, latitude of Neptune, 1846–1968. Reprinted, with permission, from Seidelmann *et al.*, 1971.

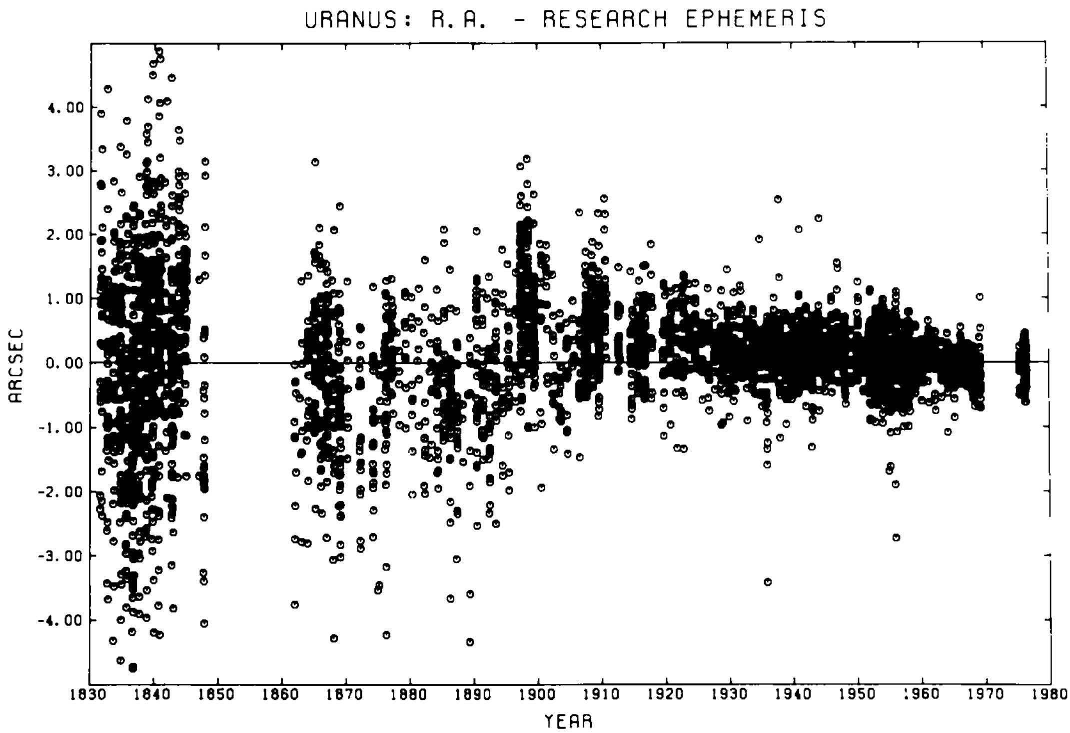

FIG. 3. O − C, right ascension of Uranus, 1832–1978.

satisfy both the prediscovery and modern observations of Neptune (Clemence and Brouwer, 1951). Brouwer's 1955 analysis produced a mass of 0.8 that of the Earth for Pluto, but he pointed out that systematic deviations remained in the observation residuals of both Neptune and Uranus. Direct measurement of the diameter of Pluto as 5928 km by Kuiper (1950), and determination of an upper limit of the diameter of Pluto of 6400 km by Halliday *et al.* (1965) taken in combination with a mass equal to one Earth mass yielded the uncomfortably high value for the density of Pluto of about 40 g/cm.

In his solution for the mass of Pluto, Wylie (1942) pointed out the difficulty of trying to separate the effect of Pluto on Nepune's motion from corrections to the orbital elements of Neptune. With the greater availability of high-speed computing equipment in the 1960s it became feasible for us to approach the problem of the mass determination in a slightly different manner. By the generation of a number of numerical theories of the motion of Neptune, incorporating various estimates of the mass of Pluto, these theories were then adjusted to observations spanning the period 1846–1938. Analysis of the ability of these orbits to represent the observed motion of Neptune in the following 30 years was used as a criterion in selecting the best estimate of the mass of Pluto. Using a limited data set, we found (Duncombe *et al.*, 1968) a value for the mass of Pluto of about 0.18 Earth mass. Later, utilizing the same method and a full data set (Seidelmann *et al.*, 1971), we derived the value of the mass of Pluto as 0.11 Earth mass. At this same time Ash *et al.* (1971) estimated from their comprehensive solution, an upper limit of 0.08 Earth mass. The value of 0.11 Earth mass for the mass of Pluto, with the measure of the diameter of Pluto given above, yielded a density of

Pluto of 4.86 g/cm^3, or about $\frac{8}{10}$ths of the Earth's density. Using a mass of $\frac{1}{10}$th that of the Earth for Pluto, and adjusting the numerical theory to the observations of Neptune on the interval 1846–1938, Figs. 1 and 2 illustrate the extension of this theory forward into the period 1938–1968. The observations seem reasonably well represented, although slight systematic trends in both longitude and latitude remain. Evidence that this value of the mass of Pluto was too high came from Cruikshank *et al.* (1976), when from measures of the surface composition and albedo they estimated a mass of Pluto of only a few thousandths that of the Earth. Further evidence was provided in 1978 by Christy and Harrington (1978), with the discovery of the satellite of Pluto, which the discoverer has designated as Charon. From the motion of this satellite (Harrington and Christy, 1980), a value of the mass of Pluto of 0.002 Earth mass has been derived, and this must be considered the most definitive to date.

This recent determination of the mass of Pluto raises several interesting dynamical questions. What did Lowell and Pickering see in the observation residuals of Uranus and Neptune? Lowell assumed in his predictions a mass for planet X of 3000 times that of the recently derived mass of Pluto, while Pickering assumed a value of 1000 times the mass in his predictions of the position of planet O. Yet at the time of the discovery of Pluto, the predictions of Lowell and Pickering agreed with each other within 0.6° of longitude and were both within 6° of longitude of Pluto. In discussing the observational residuals of Uranus and Neptune as compared to numerical theories of the five outer planets, incorporating a value of the mass of Pluto 500 times the recently derived value, Brouwer (1955) noted that there were anomalous trends in

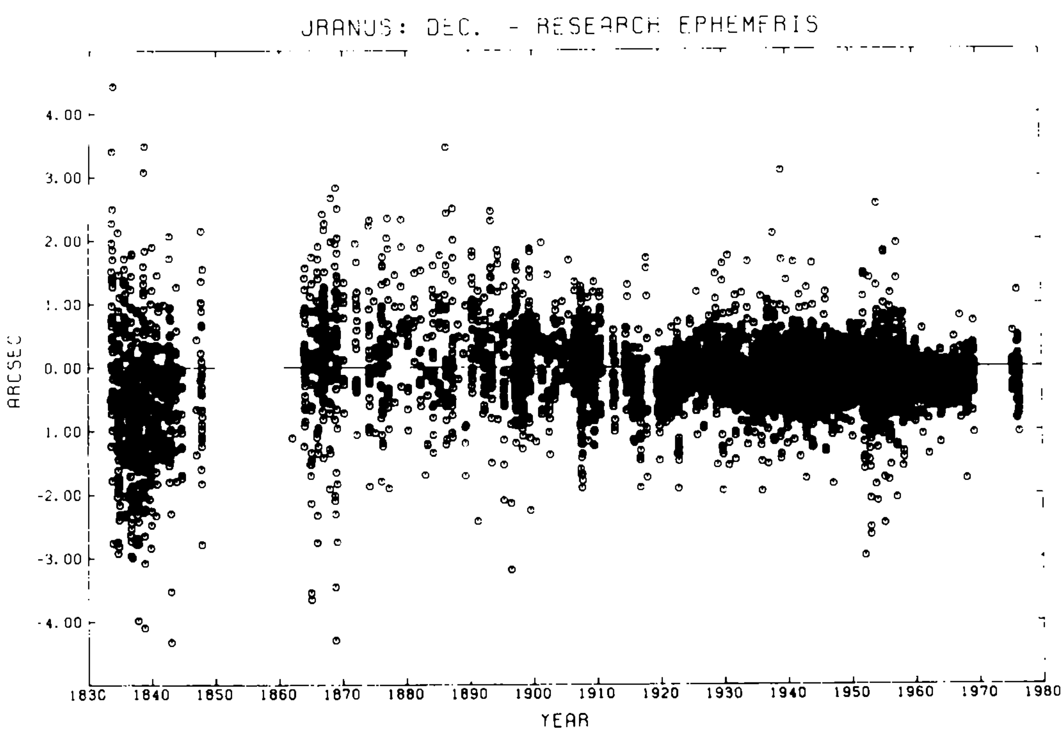

FIG. 4. O – C, declination of Uranus, 1832–1978.

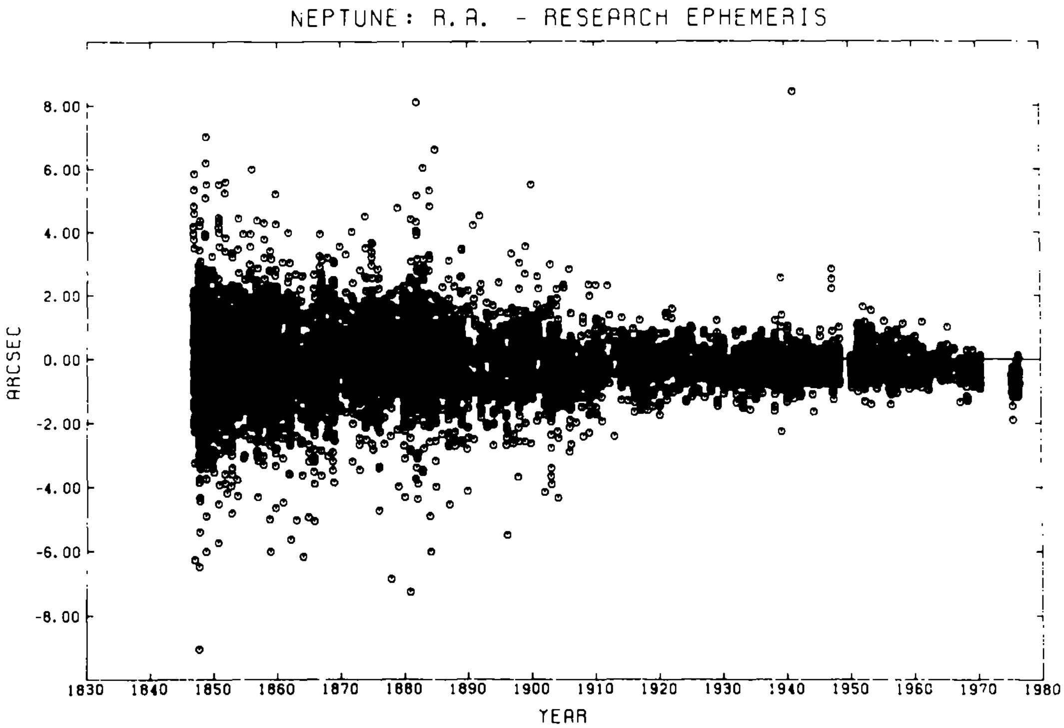

FIG. 5. O − C, right ascension of Neptune, 1846–1978.

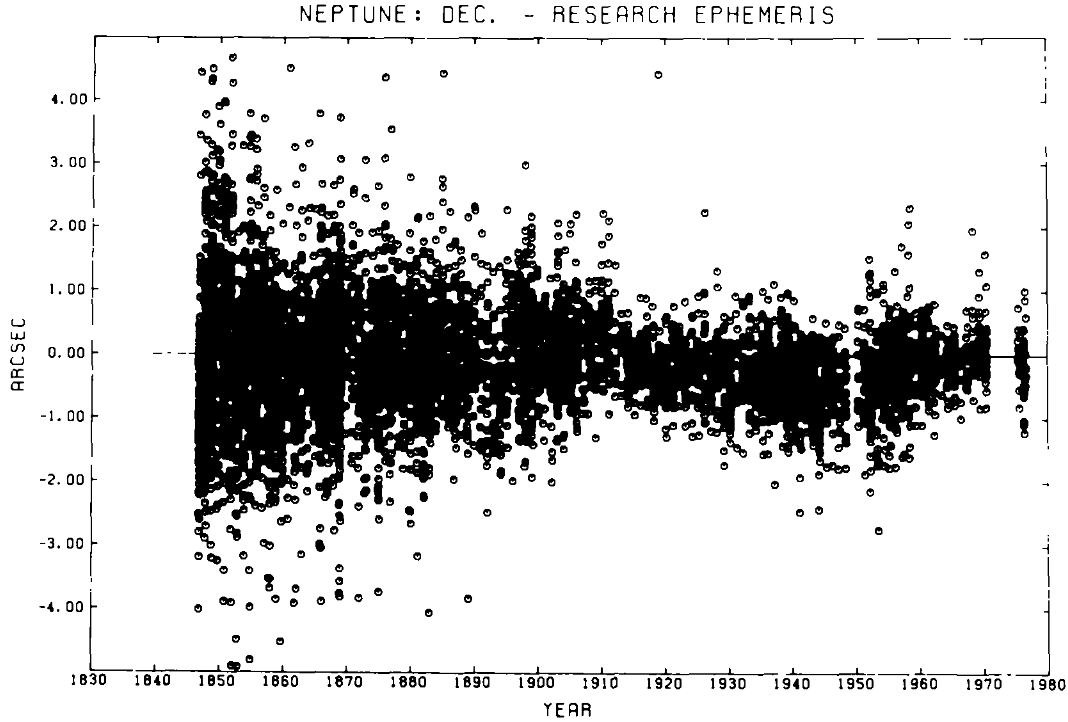

FIG. 6. O − C, declination of Neptune, 1846–1978.

the residuals of both of these planets. In our work in 1971, incorporating a mass of Pluto 50 times the recently derived value, we felt that we had obtained a more lasting representation of the observations of the outer planets. The passage of time has proven otherwise. Exhibited in Figs. 3, 4, 5, and 6 are the right ascension and declination residuals of Uranus and Neptune, respectively, as derived from comparison with our 1971 theories. While the theory represents the right ascension of Uranus, the declination residuals exhibit an apparent secular trend. For Neptune the representation of the right ascension shows a secular run off in the past 10 years. Also the declination residuals show a periodic trend which may arise from a secular difference due to the least-squares fitting of observations that do not cover a complete orbit.

Two conclusions can be drawn from this evidence: (1) while all credit must be given to Percival Lowell for initiating, and providing the impetus for, a search for planet X, the subsequent discovery of Pluto seems due entirely to the thorough and painstaking search made by Clyde Tombaugh. In 1968 we noted that "the discovery of Pluto must be considered as being due more to an intensive astrometric search than to any prior knowledge of position from gravitational theory." In view of the further reduction in the mass of Pluto, this statement is even more pertinent today. (2) The new mass of Pluto effectively removes it as a source for the anomalous residuals observed in the motion of Uranus and Neptune. Apparently, our model of the outer solar system remains incomplete.

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