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THE MASS OF (1) CERES FROM PERTURBATIONS ON (348) MAY

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ABSTRACT

The most promising ground-based technique for determining the mass of a minor planet is the observation of the perturbations it induces in the motion of another minor planet. This method requires careful observation of both minor planets over extended periods of time. The mass of (1) Ceres has been determined from the perturbations on (348) May, which made three close approaches to Ceres at intervals of 46 years between 1891 and 1984. The motion of May is clearly influenced by Ceres, and by using different test masses for Ceres, a search has been made to determine the mass of Ceres that minimizes the residuals in the observations of May.

Introduction

The masses of the largest minor planets are rather poorly known. Traditionally, the masses of the major planets were obtained by observing their mutual perturbations or by observing their satellite systems. These methods are not easily applicable to minor planets: no minor planets are known to have satellites; the minor-planet perturbations on any of the major planets are negligible (from a ground-based viewpoint, except by tracking spacecraft); and the mutual minor-planet perturbations generally are small. However, the mutual-perturbation method, when applied to suitable objects, is the best ground-based method currently available for determining minor-planet masses. The best circumstances for using this method occur when one of the minor planets is large compared to the other, when the two objects make close, periodic approaches to each other, and when both have long observational histories.

A suitable pair of objects with long observational histories that make periodic close approaches to one another are (1) Ceres and (348) May: to 0.0816 AU in April 1938 and to 0.0424 AU in September 1984 (a moderately close-approach to 0.2006 AU occurred in December 1891, just prior to May's discovery). The orbital inclinations and nodal longitudes of Ceres and May are broadly similar, and since both orbits are of low eccentricity with semi-major axes differing by only 0.2 AU, encounters between the two tend to be quite prolonged: during the 1938 encounter May was within 0.1 AU of Ceres from December 1937 until July 1938; in 1984 the corresponding dates are February 1984 and March 1985. In addition, May is so small that its perturbing effect on Ceres can be neglected.

The first direct measurement of the mass of a minor planet was made by Hertz (1966), who, noting that (4) Vesta and (197) Arete approached each other to within a few hundredths of an AU every 18 years, determined the mass of Vesta to be $(1.17 \pm 0.10) \times 10^{-10} M_{\odot}$. This value was later revised to $(1.20 \pm 0.08) \times 10^{-10} M_{\odot}$ (Hertz, 1968). Prior to this determination, the masses of minor planets were estimated on the basis of measured or presumed diameters and presumed densities.

The suggestion that the mass of Ceres, M_c, might be determined from the perturbations it induced in the motion of a smaller body was made by Gauss. In 1802, shortly after the discovery of Pallas, he noted the close approach of the orbits of Ceres and Pallas at the descending node of the latter, and expressed the hope that the masses of both bodies might be determined from their gravitional influences on each other.

From consideration of the perturbations on Pallas by Ceres, Schubart (1970) derived $M_c = (6.7 \pm 0.4) \times 10^{-10} M_{\odot}$. From the perturbations by Ceres on Vesta, Schubart (1971) derived $M_c = 5.1 \times 10^{-10} M_{\odot}$, and combined this result and his 1970 value to obtain $M_c = (6.0 \pm 0.7) \times 10^{-10} M_{\odot}$. Schubart (1974), using a slightly different set of Pallas observations, refined this value to $M_c = (5.9 \pm 0.3) \times 10^{-10} M_{\odot}$. Landgraf (1988), again considering perturbations on Pallas, found $M_c = (5.0 \pm 0.3) \times 10^{-10} M_{\odot}$. Standish and Hellings (1989), considering the perturbations on Mars determined from the highly accurate ranging data from the Viking landers, found $M_c = (5.0 \pm 0.2) \times 10^{-10} M_{\odot}$.

For some time, E. Bowell, Lowell Observatory, has been recalculating the orbits of the old numbered minor planets on a regular basis. Bowell was unsuccessful in his attempt to represent the motion of May by considering perturbations by Mercury to Pluto, and he brought the matter to the attention of the author at the Minor Planet Center (hereafter referred to as MPC). After several attempts to obtain a reasonable orbit failed, the author realized that Ceres might be perturbing May significantly. Since the presumed effect of

Ceres was quite large (more than 100″ in right ascension between 1892 and 1989), it was reasoned that the perturbations on May might be a rather sensitive indicator of the mass of Ceres. This hypothesis could not be tested until development versions of perturbation programs designed to work in the J2000.0 system were completed in late 1990, as the B1950.0 versions in use previously at the MPC were not designed to handle Ceres as a perturbing body.

The Observations

(348) May was discovered by A. Charlois in Nice on November 18, 1892. It was followed until January 1893 and was recovered by J. Palisa in Vienna in March 1894. It was followed there and at Nice for a month, but was not observed again until 1905. Observations seem to have been made at almost every opposition subsequent to 1910.

It is known that the archive of minor-planet observations at the MPC is fragmentary for observations made before 1939. A project to include more pre-1939 material in the archive is progressing. Efforts are also being made to encourage the remeasurement of plates for which only approximate positions have been previously reported.

A literature search was undertaken to obtain pre-1939 observations of May, so the observed arc could be extended back to the discovery opposition. Good series of observations made at Algiers were located. It was possible to rereduce the micrometric observations using the planet-minus-comparison offsets as given in the original publication and modern comparison-star positions. The rereduction of micrometer measures is a tedious task to do by hand, so the process was automated. The program that was written to accomplish this task, COMPSTAR, will also be used to handle the automatic rereduction of micrometric measures that are encountered in the course of the long-term project to expand the MPC archives.

A number of positions of (348) May in the MPC archive were approximate positions. Such positions are useless for orbit determination, and their only purpose is to show that there is a plate available for remeasurement. Precise measurements were desired for the series of approximate positions obtained at the Goethe Link Observatory, Indiana, and Turku, Finland. The plates taken in Indiana are now archived at the Lowell Observatory. The Indiana plates containing images of May were remeasured by B. A. Skiff, following a request to E. Bowell, and the relevant Turku plates were remeasured by A. Niemi, following a request to L. Oterma. A search of the Harvard plate-archives by C. Y. Shao led to the identification of a number of images of May from the 1920s and 1930s, and measurement of these images was undertaken by A. J. Noymer.

At the request of the author May was put on the observing program of the Oak Ridge Observatory. A number of observations at the 1991 opposition were obtained, extending over an arc of three months. A new orbit for May, computed in the J2000.0 system, published recently in the *Minor Planet Circulars* (Williams, 1991) includes these new observations.

The Orbits

A number of different orbits were calculated for May, considering the perturbations by Mercury to Neptune plus Ceres, using a different mass for Ceres in each orbit. The same observations were used in each calculation: 75 observations at 29 oppositions, 1892-1991. These observations showed reasonable residuals from a preliminary orbit calculation.

The first mass used was the 1976 IAU-recommended value, $5.9 \times 10^{-10} M_{\odot}$. Solutions were also done using masses ranging from (in units of $10^{-10} M_{\odot}$) 4.0 to 5.6. The r.m.s. residuals for each orbit solution are given below:

Mass ($\times 10^{-10} M_{\odot}$)	0	4.0	4.2	4.4	4.6	4.7	4.8	4.9	5.0
r.m.s. residual (″)	2.97	1.23	1.19	1.16	1.15	1.14	1.14	1.14	1.15

Mass ($\times 10^{-10} M_{\odot}$)	5.2	5.4	5.6	5.9
r.m.s. residual (″)	1.16	1.19	1.23	1.31

It can be seen from the table that the IAU-recommended value is too large. The mass of Ceres and its mean error were determined by the method of Herget (1972): this gave $(4.80 \pm 0.22) \times 10^{-10} M_{\odot}$.

As a test to see whether the motion of May was affected by any large minor planet other than Ceres, the influence of (511) Davida was examined (May and Davida can approach to within 0.05 AU). Assuming that Ceres and Davida have the same density, and using the diameters given by Tedesco (1989), a reasonable estimate for the mass of Davida was $3 \times 10^{-11} M_{\odot}$. The orbit of May was recalculated twice: once considering perturbations by Venus to Neptune plus Ceres; and once including perturbations by Davida. Comparison of the residuals of both solutions showed small differences of $\sim 0''.4$ in right ascension by 1892. This is only 0.4% of the difference caused by Ceres and does not significantly alter the estimate of the error of the derived mass of Ceres.

Preliminary Conclusions and Further Work

A *preliminary* determination of the mass of (1) Ceres, deduced from the perturbations on (348) May, is $(4.80 \pm 0.22) \times 10^{-10} M_{\odot}$.

A request has been made to L. D. Schmadel and S. Röser of the Astronomisches Rechen-Institut, Heidelberg, to secure the remeasurement of the relevant plates taken by Wolf and Reinmuth.

A search has also been made to locate other minor planets that approach Ceres periodically. Many objects were found to have *orbits* that approach Ceres *very* closely. This extensive list can be shortened by considering the observed arc of each object, whether there are any approaches to Ceres during the observed arc and, if there are, the number and duration of these approaches. Although this is quite time-consuming, several promising candidates have been identified, and study of the motion of these objects may help to constrain the mass of Ceres further.

Object	Date of approach	Δ_{min} (AU)
(32) Pomona	1975 Nov.	0.0250
(58) Concordia	1929 Sept.	0.0408
(84) Klio	1990 Mar.	0.0417
(91) Aegina	1973 Sept.	0.0332
(135) Hertha	1907 Feb.	0.0529
(165) Loreley	1909 May	0.0824
	1937 Jan.	0.0387
	1964 Sept.	0.0966
(203) Pompeja	1948 Aug.	0.0165
	1969 Feb.	0.0781
(255) Oppavia	1955 Nov.	0.0804
	1958 Apr.	0.0418
(324) Bamberga	1944 Mar.	0.0207

A recent independent study of the motion of (203) Pompeja (Goffin, 1991) determined the mass of Ceres to be $(4.7 \pm 0.3) \times 10^{-10} M_{\odot}$. Although it has been clear for some time that the influence of Pluto is negligible on the motion of most minor planets and that Ceres should be included as a perturbing body when orbits are computed with full perturbations, it is important that all orbit computations are done using a standard value for the mass of Ceres. Commission 20 of the IAU, at a session at the 1991 IAU General Assembly in Buenos Aires, suggested the use of $5.0 \times 10^{-10} M_{\odot}$ as the mass of Ceres. This is the value that is now in use at the MPC.

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