NEW OSCULATING ORBITS FOR 110 COMETS AND ANALYSIS OF ORIGINAL ORBITS FOR 200 COMETS

B. G. MARSDEN AND Z. SEKANINA

Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138

E. EVERHART

Department of Physics, University of Denver, Denver, Colorado 80208

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ABSTRACT

New osculating orbits are presented for 110 nearly parabolic comets. Combining these with selected orbit determinations from other sources, we consider a total of 200 orbits where the available observations yield a result of very good (first class) or good (second class) quality. For each of these, the original and future orbits (referred to the barycenter of the solar system) are calculated. The Oort effect (a tendency for original \(1/a\) values to range from 0 to \(+100 \times 10^{-6}\) AU\(^{-1}\)) is clearly seen among the first-class orbits but not among the second-class orbits. Modifications in original \(1/a\) values due to the effects of nongravitational forces are considered.

I. INTRODUCTION

The main reason for this study is to assemble high-quality dynamical data on comets with nearly parabolic orbits (hereafter called nearly parabolic comets). Specifically, we derive heliocentric orbits for osculating epochs near perihelion passage and then calculate the "original" and "future" barycentric orbits (referred to the center of mass of the solar system) before and after the comets are subject to appreciable planetary perturbations. In an earlier paper (Marsden and Sekanina 1973) we established that the "Oort effect"—the tendency for the original reciprocal semimajor axes \((1/a)_{\text{orig}}\) to cluster around small positive values—is extremely pronounced in the case of comets of large perihelion distance \(q\). We found that 17 of the 22 best-determined nearly parabolic orbits with \(q > 2.2\) AU had values of \((1/a)_{\text{orig}}\) clustering around +34 units (1 unit = 10\(^{-6}\) AU\(^{-1}\)), and none had \((1/a)_{\text{orig}} > +700\) units. Since planetary perturbations typically change \(1/a\) by several hundred units during one revolution about the Sun, we were forced to conclude, following Oort, that the great majority of these comets were making their first passage through the inner part of the solar system.

The computations presented here are restricted to comets with revolution periods greater than 200 yr. Short-period comets, particularly those with periods less than about 20 yr, represent a different situation. Their recent orbital evolution is primarily due to the direct action of Jupiter (Everhart 1972, 1976).

Oort's (1950) own initial investigation of the distribution of \((1/a)_{\text{orig}}\) was based on 19 nearly parabolic comets, only four of which had \(q > 2.2\) AU. Our previous study was restricted to comets of large \(q\) in order to minimize the influence of nongravitational forces. Nevertheless, if there is indeed a difference in the Oort effect for comets of small and large \(q\), it is now necessary to determine the orbits of nearly parabolic comets of small \(q\) as reliably as possible. If individual results cannot be trusted, we remark that since the radial component of the nongravitational force is expected to be positive outward from the Sun, the values of \(1/a\) should be systematically in error, in the sense that the original orbits will appear to be more hyperbolic than they really are (Marsden, Sekanina, and Yeomans 1973).

II. NEW GRAVITATIONAL ORBIT DETERMINATIONS

In Table I we give the results of our orbit determinations for 110 single-apparation comets. These computations have been made by the first two authors of this paper, perturbations by all nine planets being taken into account. Although in many instances our calculations merely confirm those made previously by other investigators, they are nonetheless of value because the mean errors of \(1/a\) are derived in a uniform way. Until a redetermination is made one does not know whether it is possible to rely on an earlier computation. For example, the previous result for the well-observed comet 1907 IV by Baehr (1933) turned out to be very accurate, although planetary perturbations were not allowed for during the arc of more than 12 months covered by the observations. On the other hand, the orbital elements for comet 1912 II by Peisino and de Caro (1931) are completely erroneous, in part because these authors did not realize that the reference-star position for the crucial final observation required correction by exactly 10° in right ascension.

To this sample of 110 orbits we add 20 of the large-\(q\) orbits given in Table I of Marsden and Sekanina (1973) (except that those of comets 1947 VIII, 1950 I, and 1972 IX are recalculated here), as well as the orbits of comets...
III. ACCURACY OF THE ORBITS

We have classified the accuracy of the orbit determinations according to a quantity $Q$ defined by

$$Q = \frac{1}{2}(L + M + N) + \delta,$$

where the integers $L$, $M$, and $N$ depend, respectively, on the mean error of the determination of the osculating $1/a$, the span of time covered by the observations, and the number of planets whose perturbations were taken into account, following the scheme in Table II. The quantity $\delta$ is taken to be $\frac{1}{2}$ or 1 in order to make $Q$ integral, and hence $0 \leq Q \leq 9$. If $Q = 9$, 8, or 7, the orbit is put in class I ($Q = 9$ or 8 being subdivided into class IA, $Q = 7$ into class IB), and if $Q = 6$ or 5 it is in class II ($Q = 6$ corresponding to class IIA, $Q = 5$ to class IIB). Cases where $Q < 5$ (which include all the parabolic approximations and orbits where no perturbations were considered) are not of interest to us here. The above criterion for establishing accuracy classes for orbits will favor our own computations, where $N = 3$, and it will also favor comets of large $q$, where frequently $L > 4$ and $M > 5$, a combination that will lead to a class I orbit. We feel that these biases are appropriate and so have refrained from adding further criteria to Eq. (1), such as direct dependence on $q$, the range in true anomaly, the mean residual, consideration of the number of observations used and their distribution with time, and whether normal places were utilized.

The criterion $Q$ yields 111 orbits of class I and 89 orbits of class II. Although further orbit computations will cause these numbers to increase as comets are observed in the future, it is unlikely that additional recalculations of the orbits of past comets (66 of these results are from various earlier calculations) will cause more than a few changes and additions to these classifications.

IV. ORIGINAL AND FUTURE ORBITS

The heliocentric osculating values $(1/a)_{osc}$ can be converted to the corresponding barycentric $(1/a)_{or}$ and $(1/a)_{fut}$ by adding to them the quantities $-u_a$ and $+u_a$, defined and listed for the comets of the 19th and 20th centuries by Everhart and Raghavan (1970). In that compilation the departure from parabolic motion was ignored, and in cases where this departure is relatively large, the results require significant correction. Accordingly, the third author has recalculated the values of $-u_a$ and $u_a$. The present method involves a numerical integration of the path of the comet accurate to the 15th order in the step size and taking into account the perturbations by all nine planets. The comet is followed from its position at the epoch backward and forward in time until it is 60 AU from the Sun. The integrator used for these barycentric $(1/a)_{or}$ and $(1/a)_{fut}$ calculations is an implicit single-sequence method (Everhart 1974a, 1974b), which is very efficient for this purpose. In the several cases where the first two authors checked these results, the difference in $(1/a)_{or}$ was rarely as large as 0.1 unit.

Table III includes the resulting 200 values of $(1/a)_{or}$ and $(1/a)_{fut}$, arranged in order of $q$ and separated by comet class. In accordance with the resolution adopted by IAU Commission 20 in 1970 (Roemer 1971), $(1/a)_{osc}$ (given here with its mean error) and the quantities $u_a$ and $u_a$ are in each case referred to the standard 40-day Julian date closest to perihelion passage. The values of $u_a(p)$ and $u_a(p)$ that correspond to an osculation epoch exactly at perihelion passage are also listed. Asterisks in the final column identify the 12 class I and 54 class II orbits that were not determined as part of the sample mentioned in Sec. II. These other orbits are generally those tabulated in the comet catalog (Marsden 1975a), except that the class II orbits for comets 1840 IV, 1844 II, 1847 II, 1849 II, and 1850 I are from recent calculations by Buckley (1976). Where necessary the starting elements were adjusted to the official osculation epochs.

Even a cursory examination of the class I values of $(1/a)_{or}$ given in Table III confirms that the Oort effect is much more obvious for the comets of largest $q$, which enforces our earlier conclusion (Marsden and Sekanina 1973) that most comets of $q \geq 2$ AU do not survive as readily discoverable objects after their first approaches to the Sun. We remark that the largest $(1/a)_{or}$ among nearly parabolic comets of $q > 2.0$ AU belongs to the highly unusual comet 1962 VIII, which was extremely active at large heliocentric distances. The largest class I $(1/a)_{or}$ for $q > 3.0$ AU refers to comet 1927 IV, which was intrinsically very bright and also active far from the Sun. We note that among class I comets the only entry for $(1/a)_{or}$ +89 and +227 units refers to 1908 III, another physically unusual comet. The gap suggests that it is reasonable to limit "new" comets, i.e., comets that are probably making their first passage through the inner part of the solar system, to those with $(1/a)_{or} < +100$ units.

V. STATISTICAL ANALYSIS OF ORIGINAL ORBITS

Table IV gives a statistical analysis of the $(1/a)_{or}$ data in Table III. The upper section refers to the class I orbits, the lower section to the class II orbits. In each range of $q$ the first three columns give some indication of the spread in $(1/a)_{or}$, the quantities listed being the means (with each orbit regarded as of unit weight) of the overlapping lower, middle, and upper halves of the $(1/a)_{or}$ distribution. The mean $(1/a)_{or}$ and the number of "new" comets are also tabulated.
1978AJ 83 . . . 64M

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Note to Table I

For each entry, the first line gives the comet's designation, the number of observations utilized, and the mean residual of the orbit determination. Successive lines then give the epoch of occultation and time of perihelion passage (each in ephemeris time with only the last two digits of the year given); the argument of perihelion, longitude of the ascending node, and inclination (in degrees and referred to the ecliptic and mean equinox 1950.0); the perihelion distance (in AU); and the eccentricity. The errors are mean and are given in units of the last decimal place quoted. The last line gives the interval of time covered by the observations (the year again being referred to its last two digits).

Table II Quantities for establishing accuracy classes.

<table>
<thead>
<tr>
<th>Time span of observations</th>
<th>No. of planets</th>
<th>No. of comets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-3</td>
<td>12355</td>
<td>99</td>
</tr>
<tr>
<td>0.75-1.5</td>
<td>12355</td>
<td>99</td>
</tr>
<tr>
<td>12-22 days</td>
<td>7-9</td>
<td>3-6</td>
</tr>
<tr>
<td>7-11</td>
<td>3-6</td>
<td>1-2</td>
</tr>
<tr>
<td>3-6</td>
<td>1-2</td>
<td>0</td>
</tr>
</tbody>
</table>

Including parabolic orbits.

From the earlier tabulation of \( w_a \) and \( w_b \) values (Ev-erhart and Raghavan 1970), it follows that the mean change \( w_a + w_b \) in \( \ell/\beta \) during one revolution of a comet around the Sun is close to zero. On the other hand, the mean change for the 50% of the comets whose orbits are made more elliptical is about 400 units. This average perturbation decreases somewhat with increasing distance from the Sun, as indicated in the column labeled "old". The number of "old" comets is also indicated.
For each entry are given the perihelion distance \( q \) (in AU) and the inclination \( i \) (in degrees and referred to the ecliptic and mean equinox 1950.0). The quantities \( u_q = (1/a_{\text{helioc}} - 1/a_{\text{ort})} \) and \( u_i = (1/a_{\text{helioc}} - (1/a_{\text{ort}}) \) are also tabulated with respect to the perihelion \( (p) \) and with respect to the 40-day date closest to the time of perihelion passage; then come \((1/a_{\text{helioc}})\) (with respect to this 40-day date) and its mean error, and the resulting \((1/a_{\text{helioc}})\) and \((1/a_{\text{ort}})\); all these numbers are in units of \(10^6\) SU\(^{-1}\). The orbits are listed according to increasing \( q \). The subdivision of these classes; an asterisk (*) identifies those orbits not calculated or recalculated as part of this program.

Note to Table III

<table>
<thead>
<tr>
<th>Class I</th>
<th>( q ) (AU)</th>
<th>( i ) (deg)</th>
<th>( u_q )</th>
<th>( u_i )</th>
<th>( 1/a_{\text{helioc}} )</th>
<th>( 1/a_{\text{ort}} )</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1947 I</td>
<td>0.025</td>
<td>144.6</td>
<td>1946 I</td>
<td>0.021</td>
<td>139.1</td>
<td>1945 I</td>
<td>0.024</td>
</tr>
<tr>
<td>1947 II</td>
<td>0.140</td>
<td>131.4</td>
<td>1946 II</td>
<td>0.121</td>
<td>127.3</td>
<td>1945 II</td>
<td>0.133</td>
</tr>
<tr>
<td>1947 III</td>
<td>0.272</td>
<td>126.7</td>
<td>1946 III</td>
<td>0.241</td>
<td>122.1</td>
<td>1945 III</td>
<td>0.253</td>
</tr>
<tr>
<td>1947 IV</td>
<td>0.446</td>
<td>129.7</td>
<td>1946 IV</td>
<td>0.415</td>
<td>125.1</td>
<td>1945 IV</td>
<td>0.427</td>
</tr>
<tr>
<td>1947 V</td>
<td>0.640</td>
<td>136.1</td>
<td>1946 V</td>
<td>0.607</td>
<td>131.5</td>
<td>1945 V</td>
<td>0.619</td>
</tr>
<tr>
<td>1947 VI</td>
<td>0.875</td>
<td>140.0</td>
<td>1946 VI</td>
<td>0.842</td>
<td>135.4</td>
<td>1945 VI</td>
<td>0.854</td>
</tr>
</tbody>
</table>

For the original and future orbits.

Table III.

Original and future orbits.

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Cometary fading apparently is also responsible for the complete absence of "old" comets with \( q > 2 \) AU in class II and their virtual absence in class I. Consequently the spread in \( \langle 1/a \rangle \) orig is considerably larger for comets with \( q < 2 \) AU, and it is largest and the proportion of "old" comets greatest when \( 0.5 < q < 1.5 \) AU. Of the six "old" comets having \( q < 0.5 \) AU, three are members of the Kreutz Sun-grazing group and are thus highly selective objects. One can speculate that the relative paucity of "old" comets of \( q < 0.5 \) AU can be attributed to the rapid dissolution or disintegration of comets that pass so close to the Sun, although selection effects in the discovery rates might also be involved.

Let us estimate the average number of returns made by the "old" comets. If we compare Monte Carlo exact orbit integrations, which were used to trace the average period of observable long-period comets as a function of the number of returns (Everhart 1976, Fig. 3, curve B), with the mean revolution period for the "old" comets in Table III, we find that they have completed, on the average, only 30 and 70 returns of classes I and II, respectively. We may conclude, therefore, that really old comets (by number of revolutions, not by years!) are relatively rare. Again, the observability of such "wornout" comets obviously is a factor.

The fact that the mean \( \langle 1/a \rangle \) orig of "new" comets tends to be negative at small \( q \) is presumably due to the influence of nongravitational forces. In order to gain greater insight into the variation of the original semi-major axes of gravitational orbits with perihelion distance, we grouped the "new" class I comets into a number of overlapping intervals in \( q \). The interval lengths were wider for greater \( q \). Averaging \( \langle 1/a \rangle \) orig in each group and plotting it versus \( 1/q \), we obtained the result shown in Fig. 1. The relation is remarkably linear, satisfying an empirical fit:

\[
\langle 1/a \rangle \text{ orig} = -46.3 - 23.7 (1/q) \text{ units.}
\]

\[
\pm 1.3 \quad \pm 0.6 \text{ (m.e.)}
\]

The dip between \( q = 2 \) and 3 AU is much less conspicuous than in Table IV, because the effect of comet 1898 VIII, to which it is due, has now been suppressed more appreciably. The scatter in \( \langle 1/a \rangle \) orig, corrected for the scatter in \( 1/q \), is plotted versus \( 1/q \) in Fig. 2. It increases steeply with \( 1/q \) for \( q > 0.7 \) AU and much more slowly at smaller \( q \).

Equation (2) quantitatively demonstrates that neglect of the nongravitational effects does indeed result, on the average, in seemingly more hyperbolic orbits; a comet from the Oort cloud with \( q \approx 0.5 \) AU is equally likely to have an elliptical or hyperbolic original orbit as determined from a purely gravitational solution.

The existence of many more class II negative \( \langle 1/a \rangle \) orig values might suggest that, on the average, these comets have been subjected to much larger nongravitational forces. We have already discussed (Marsden, Sekanina,
Table V. Nongravitational orbital elements.

<table>
<thead>
<tr>
<th>Comet</th>
<th>( A_1 )</th>
<th>Mean residual</th>
<th>( (1/a)_{\text{orig}} ) (units)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1899 I</td>
<td>+2.9 ± 0.4</td>
<td>1.72</td>
<td>-46 ± 91</td>
<td>Comet split</td>
</tr>
<tr>
<td>1946 I</td>
<td>+3.0</td>
<td>1.28</td>
<td>-5</td>
<td>( A_1 ) assumed</td>
</tr>
<tr>
<td>1948 I</td>
<td>+0.8 ± 0.2</td>
<td>1.78</td>
<td>+47 ± 18</td>
<td></td>
</tr>
<tr>
<td>1952 I</td>
<td>+5.0</td>
<td>1.16</td>
<td>+86</td>
<td>( A_1 ) assumed</td>
</tr>
<tr>
<td>1955 V</td>
<td>+1.5 ± 0.8</td>
<td>1.79</td>
<td>-284 ± 28</td>
<td>Comet split</td>
</tr>
<tr>
<td>1975 XI</td>
<td>+0.8 ± 0.5</td>
<td>1.44</td>
<td>-154 ± 88</td>
<td></td>
</tr>
<tr>
<td>1975q</td>
<td>+0.5 ± 0.1</td>
<td>1.73</td>
<td>+158 ± 37</td>
<td></td>
</tr>
</tbody>
</table>

Note to Table V
This table is in the same format as Table I, except that the last two lines under each entry give the radial and transverse nongravitational parameters \( A_1 \) and \( A_2 \), described by Marsden, Sekanina, and Yeomans (1973), adopting a scaling distance \( r_0 \) of 2.808 AU.

and Yeomans (1973) the likelihood that nongravitational forces were acting on two of these comets (1960 II and 1971 V). Comet 1944 I is not listed here, but that object, observed for only a short while and only because of its proximity to Earth, might have been subject to extremely large nongravitational forces (Marsden, Sekanina, and Yeomans 1973). Since these forces presumably represent relative mass loss, 1944 I must have been a very small comet. According to Vsekhsyvatyskij (1958) the total absolute magnitude of this comet was \( H_{10} = 10.7 \), putting it among the intrinsically faintest (and presumably least massive) 5% of all known nearly parabolic comets. Similarly, comets 1975q [with the largest negative \((1/a)_{\text{orig}}\) values in Table III] and 1959 III both had \( H_{10} \gtrsim 10 \) (Marsden 1975b; Vsekhsyvatyskij 1966), whereas the orbit interpretation for the remaining comet having \((1/a)_{\text{orig}}\) more negative than \( -200 \) units (i.e., 1955 V) is complicated by the splitting of this object.

VI. Nongravitational orbit solutions
We have already remarked that all the orbits listed in Table I are from gravitational solutions. For four of the comets (1957 III, 1960 II, 1970 II, and 1971 V) we previously also made nongravitational solutions, demonstrating that one need not accept the three apparently negative \((1/a)_{\text{orig}}\) values (Marsden, Sekanina, and Yeomans 1973). These nongravitational orbits (which have in any case recently been improved) are listed for reference in Table V, together with nongravitational orbits for four other comets—1886 I, 1915 II, 1954 X, and 1974 III—where these solutions caused insignificant improvements in the residuals. Comet 1915 II is another comet that split, and 1886 I is a further case where the negative \((1/a)_{\text{orig}}\) of the gravitational solution can obviously be disregarded. A slightly different solution for comet 1886 I in which the transverse component \( A_2 \) of the nongravitational force is assumed to be exactly zero yields [with the help of Eqs. (21) and (24) of Marsden, Sekanina, and Yeomans (1973)] a value of \((1/a)_{\text{orig}} = +76 \pm 10\) units. Svedstrup (1905) also suggested that comet 1886 I was influenced by nongravitational forces, although Redlich (1911) did not agree.

Nongravitational solutions have also been attempted for some of the other comets listed in Table I, but the results were either indeterminate or did not yield any significant improvement in the residuals. These results are summarized in Table VI. In all these computations \( A_2 \) was assumed to be equal to zero. Whenever a solution was actually made for \( A_1 \), this quantity turned out to be positive. Only for comet 1975 XI has \((1/a)_{\text{orig}}\) become more negative, but the change is completely masked by the large increase in mean error.

Even if we assume a rather large value of \( A_1 \) (which would not be expected for a comet of \( q \gtrsim 1.5 \) AU), we find that \((1/a)_{\text{orig}}\) for comet 1946 I remains slightly negative. This orbit is very well determined, and the
comet was relatively bright intrinsically and was not observed to experience any problems such as splitting. As for the negative \((1/a)_{\text{orig}}\) values for comets of even larger \(q\), we remarked earlier (Marsden and Sekanina 1973) on the uncertainty of the orbits of comets 1898 VIII and 1947 I, while an alternative solution for the class II comet 1904 II \((q = 1.88 \text{ AU})\), satisfying 52 observations with a mean residual \(1.83\), yields \((1/a)_{\text{orig}} = -33 \pm 105\) units.

VII. CONCLUDING REMARKS

The calculations presented here fully confirm the general correctness of Oort’s (1950) conclusions that a large number of the nearly parabolic comets are observed on their first approaches to the Sun and that fading tends to prevent comets from being rediscovered on their subsequent returns. The increased sample of high-quality orbits reenforces our previous conclusion (Marsden and Sekanina 1973) that the Oort effect is very striking for comets of large \(q\), and it allows us to estimate quantitatively the influence of nongravitational forces on the orbits of nearly parabolic comets of smaller \(q\). There is also circumstantial evidence that intrinsic fading is particularly significant for comets of very small \(q\).

Some differences are evident between the results for the orbits of class I and class II accuracy. While a semiquantitative explanation for these has been suggested, it is at the same time desirable to augment the sample of class I orbits. The improved data available in recent years for comets of large \(q\) are very encouraging, but in the future efforts should be made to obtain extended arcs of observation for all nearly parabolic comets.

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