1961AJ.....66..368R

THE ASTRONOMICAL JOURNAL VOLUME 66, NUMBER 8 OCTOBER, 1961

Astrometric Observations and Orbits of Comets

Elizabeth Roemer
U. S. Naval Observatory, Flagstaff Station

Any study of comets begins with observations of position. Crude observations may suffice for finding purposes for spectroscopic or photometric observations of brighter objects. But a large amount of information can be gained, for faint objects as well as for bright ones, by studying the motions, or orbits.

Precise study of the motions of comets has two major aspects: *observation* and *computation*. Observations of position are desired, of considerable *precision*, and extending over as long an interval of *time* as possible. To achieve either of these ends, the application of fairly large instruments is needed. For astrometric purposes comets are not to be regarded as extended objects; the advantage in scale and limiting magnitude of large telescopes is valuable.

OBSERVING PROGRAM AT FLAGSTAFF

At the Flagstaff Station of the U. S. Naval Observatory an effort is made to obtain one pair of plates during each dark of the moon of every comet within reach of the 40-inch Ritchey-Chrétien reflector. Additional observations may be made if they are likely to be useful, as, for example, in the case of newly discovered objects. This program is a modification and expansion of the type of program carried on for some time by H. M. Jeffers of the Lick Observatory, and especially by G. Van Biesbroeck at the Yerkes and McDonald Observatories. Moving objects are recorded regularly to magnitude (pg) 20.5. Since the dividing line between short-period comets and minor planets is by no means clear, certain minor planets are observed whenever the opportunity arises. Some of these minor planets may indeed be old comet nuclei. Included on the program are all the minor planets having a perihelion distance less than 1 a.u. and many of those that have a perihelion distance only slightly greater than 1 a.u., and for which ephemerides are available.

To demonstrate the extent of the program, it may be noted that 19 different comets and nine minor planets were successfully observed during the 12 months ending in June 1961. Eight returning periodic comets were reobserved first at Flagstaff, including four within 16 days in August 1960.

In making the observations, the calculated motion of the object is offset as a general practice, the plate being displaced relative to the crosshairs of the guiding eyepiece. Guiding is done by means of a star located near the edge of the field being photographed. The telescope operates at $f/6.8$, and exposures up to two hours in duration are useful. Appropriate exposure time is expecially important in astrometric investigations. Since estimates of the brightness of comets vary greatly, depending on the instrument and methods by which the observations are made, we have found it necessary to calculate our own version of predicted magnitudes, depending upon earlier observations of our own, or those of other observers using similar equipment and methods. The results of Cunningham (1951, 1952), observing with the Mount Wilson 60-inch and 100-inch telescopes, 1950 to 1953, have been especially valuable.

Bright comets, as well as faint ones, are observed regularly. Especially in bright objects is there possibility of a systematic displacement of the center of light from the center of gravity. Such a displacement leads to systematic errors in the orbit, especially in the case of such objects as periodic Comet Encke, which is usually observable, during any specific apparition, only before, or only after, perihelion passage. To the best of my knowledge, the U. S. Naval Observatory, Flagstaff Station, is the only observatory in the world at which astrometric observations of comets fainter than mag. 17 are being made regularly at the present time.

MEASUREMENT AND REDUCTION OF PLATES

Since the field of the 40-inch reflector, or of any similar instrument, is fairly small, reference stars almost invariably have to be taken from the *Astrographic Catalogue*. With the epoch of most plates of the Catalogue 40 to 60 years ago, proper motions have had an appreciable effect upon the star positions. The calculation of the plate constants of the Catalogue often involves meridian positions of reference stars from an even earlier epoch, used without application of proper motions. The great improvement in the accuracy of positions reduced from the portion of the Paris Zone for which new plate constants have been calculated by Heckmann, Dieckvoss, and Kox (1954) is particularly noteworthy. Even with reference stars taken from the *Astrographic Catalogue*, there is an appreciable difference between the magnitudes of the moving objects being investigated and those of the reference stars. Hence there is likelihood of systematic errors.

Reduction of the measures may be carried out by any of several methods: by dependences, by a modified plate constant method, or by accurate orientation of the plate in measurement and reduction by means of an assumed value of the plate scale. The dependence method, with at least six reference stars and a least-squares solution, is used for the reduction of most of the results from Flagstaff plates, the computations being executed with the IBM 650 of the U. S. Naval Observatory, Washington, D. C. In emergencies, when results are needed immediately, the plates are generally oriented accurately and the reductions carried out by

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1961AJ.....66..368R

hand at Flagstaff. In our experience these methods provide better checks in dealing with the *Astrographic Catalogue*.

CALCULATION OF ORBITS

Only very rarely has every precaution been taken in calculation of orbits to ensure that the calculations represent the actual motion of the object to the greatest possible physical accuracy. Very few of the persons doing the computing have had observational experience, especially with large instruments. They are, therefore, not always well equipped to evaluate the quality of the observations on which the computations are based, or to deal with the observations in the most effective manner. Rarely is the attempt made to reduce the observations to a consistent catalogue system, even if this can be done.

In general, a few positions carefully measured on properly exposed plates taken with an instrument of sufficient focal length and well spaced in time are worth more in practice in defining the orbit than great numbers of positions obtained only when the comet is bright. Computers would often have an easier time, without loss of precision and sometimes with gain, if an appreciable fraction of the total number of observations were simply disregarded. This can be seen in those instances in which residuals of individual observations from an improved orbit have been published in detail.

Especially for short-period comets, the effort in predictions has generally been to obtain sufficient accuracy for recovery. The efforts of the volunteer workers of the computing section of the British Astronomical Association have been especially noteworthy and valuable in making observations possible at repeated returns of the numerous members of the short-period Jupiter family of comets. Necessarily, approximations have been introduced in computing the perturbations, and some significant perturbations have been neglected, simply to keep the volume of work within bounds. Starting orbits have not always been the best available, and almost never the best possible. And, inevitably, mistakes in the calculations have occurred from time to time. Because of misunderstanding, the idea has grown that there are appreciable nongravitational forces operative, and that precise predictions of future positions of comets are impossible.

It should be noted that observations at one apparition do not, however, determine the value of the mean motion sufficiently well to expect an exact prediction at the next succeeding perihelion passage. Furthermore, the probable error in the mean motion deduced from a least-squares correction to the elements may be largely fictitious. This fact is well demonstrated by Merton's (1927) work on periodic Comet Schaumasse. A least-squares solution by G. Fayet and A. Schaumasse from the observations in 1919 gave a value of the mean daily motion, $n=439''.476\pm0''.7$. By linking the apparitions in 1911 and 1919, Merton found the value of the mean motion to be $n=446''.811$. This value of n made the predicted time of perihelion passage in 1927 some *49 days* earlier than the 1919 observations alone indicated. In spite of decidedly unfavorable circumstances the comet was recovered very close to Merton's prediction. Another example is the recovery of Comet Gale by Cunningham in 1938 some $5^h\,23^m$ west of what appeared to be the most likely place predicted on the basis of observations in 1927 (Davidson 1939).

Few orbit methods give a good indication of the real physical determinacy. One notable exception is Cunningham's method, in which a change of the coordinate system yields explicitly the deviation from great circle motion and the length of arc represented by the fundamental observations. A similar insight into the physical accuracy may be obtained by computing variational orbits, on each of which the observations may be represented. This becomes practicable now with the application of large digital computers.

The correction required to bring the predicted time of perihelion passage into accord with observation for periodic comets reobserved in 1960–61 is shown in column 3 of Table I. The total number of observed perihelion passages of each comet appears in column 2. It should be noted that if two perihelion passages have been observed and an effort made to obtain an accurate prediction, the divergence of calculations from observations is very small. The predictions for comets Reinmuth 2, Encke, and Wirtanen are examples.

TABLE I.

Comet	Obs. returns	ΔT (days)	Computer
Reinmuth 2	3	0	E. Rabe
Finlay	7	-1.2	M. P. Candy
Comas Solá	5	(small)	H. Q. Rasmusen, J. M. Vinter Hansen
Harrington	2	-0.6	C. Dinwoodie, B. G. Marsden
Brooks 2	10	(small)	A. D. Dubiago
Encke	46	0	S. G. Makover
Schwassmann-Wachmann 2	6	-0.3	H. Q. Rasmusen
Borrelly	7	$+0.2$	M. G. Sumner, M. P. Candy
Wirtanen	3	0	P. Herget
Forbes	4	$+0.5$	B. G. Marsden
Tempel 2	13	$+0.4$	B. G. Marsden

SECULAR ACCELERATIONS

It is evident from the activity photographed in the head and tail of comets that some nongravitational forces do indeed exist. But the existence of measurable nongravitational accelerations of the center of mass should be regarded as an open question. The amount of any such nongravitational accelerations is vital to theories regarding the structure of comets and their rates of disruption. See, for example, the papers by Whipple (1950), and van Woerkom (1948).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

It is a revealing experience to look critically into the published computational work, on the basis of which the existence of nongravitational secular accelerations has been asserted. Divergences from observations are quite small, and the quality of the physical parameters (such as planetary masses) and accuracy of computation that have entered into even the most precise orbits are disappointing in comparison with the size of the residuals.

As an illustrative example, let us take periodic Comet Wolf 1, 1884 III. I choose this object only because the published details of the calculations are quite complete and readily available, and also because I am responsible for all of the accurate positions obtained of this comet at its most recent return in 1958. Kamienski, who has devoted more than 50 years to study of the motion of this object lists (Kamienski 1953, 1959) 72 papers he has published to report his findings. The quality of the computations, carried out by hand methods, is quite remarkable, and this object is nearly unique in that perturbations at the most critical times have been checked by independent calculations by completely different methods. The agreement of these duplicate calculations generally has been quite good, i.e., practically to the limit of the accuracy carried. Nevertheless the small differences that do exist probably are significant in view of the size of the observational residuals, on the basis of which a secular acceleration is deduced. The system of planetary masses used involves differences in the mass of Mercury of some 50%, and of Jupiter of 0.1% from the best modern values. These differences cannot be considered negligible when the attempt is made to represent observations to 1″ accuracy.

The observed motion of P/Wolf 1 may be considered in two parts, separated by a close approach to Jupiter ($\Delta_{\min}=0.12$ a.u.) in 1922. Prior to the close approach the comet moved in an orbit of perihelion distance 1.61 a.u., and afterward in one of perihelion distance 2.45 a.u. Kamienski (1933) found it necessary to introduce an acceleration in the mean motion to represent observations in the smaller orbit:

$$\Delta n=-0\overset{\prime\prime}{.}000\,00042\,(t-t_0),$$

where $(t-t_0)$ is expressed in days from $t_0=1884$ September 24.0 BMT. The apparitions of the comet in 1925, 1933/34, and 1942 were linked with one set of elements, which, with the inclusion of perturbations due to six planets, represents also observations of the comet in 1950–51 and 1958 with maximum residuals of $-0\overset{s}{.}3$. Kamienski suggests that the residuals may be caused partly by uncertainty in the amount of perturbations by Jupiter in the mean anomaly, one part in 8000 being sufficient to reduce the residual to zero, and partly by a continuing secular deceleration. In the larger orbit Kamienski finds (1961) a value for the deceleration term of

$$\Delta n=-0\overset{\prime\prime}{.}000\,00012\,(t-t_0)$$

(with time counted in the same manner as formerly), if the deviation from theory in 1958 is attributed entirely to nongravitational forces. This acceleration, one-fourth as large as that found in the smaller orbit, is based on an observational residual of $(\alpha_0-\alpha_c)\cos\delta=-0\overset{s}{.}31=-4\overset{\prime\prime}{.}65$ on June 22, 1958.

As the person responsible for the observations, I do not feel that an acceleration deduced from such residuals is convincing. Kamienski has implied the same conclusion by suggesting that judgment should be withheld until observations can be obtained in 1967. The important point to be made here is that gravitational theory alone, with borderline numerical accuracy in computations, and physical constants capable of improvement, is adequate to represent observations over the entire time interval from 1925 to 1958 with no residual larger than 4″—a residual quite within the limits of possible observational error. There is, therefore, no evidence for appreciable nongravitational forces operating on this comet during this interval.

The observational residuals are somewhat larger for the motion in the smaller orbit, prior to 1922, and the residuals are larger for Comet Encke, which has a perihelion distance of 0.3 a.u. But both computations and observations are more sensitive to effects that lead to the appearance of a run of residuals. There is more likely to be a systematic displacement of the center of light from the center of gravity in the brighter, asymmetrical image of a comet near the sun. The time interval of steps in calculating perturbations must be shortened, leading to a rapid increase in the number of steps, and hence to an even more rapid buildup of roundoff errors in numerical integration. The approximation of a barycenter is less valid. And the perturbations by planets whose masses are subject to considerable uncertainty (Jupiter, and, formerly, Mercury and Venus) may be appreciable.

With the emphasis that has been placed recently on comets as probes in studying the interplanetary medium, and the inferences that have been drawn regarding comet models, it may not be out of order to suggest that a great deal of work needs to be done before much confidence can be placed on conclusions in these realms. A definitive study of the motion of several well-observed objects would be extremely useful. Objects suspected of a secular acceleration might supply especially interesting information. Such a study must start with a rediscussion of original observations, with efforts being made to emphasize observations carefully planned and executed with moderate- to large-sized instruments. An attempt should be made to reduce positions to a consistent catalogue system. Calculations should be carried out to full physical accuracy, and with sufficient guard figures to ensure that such factors as roundoff error in long-continued numerical integrations do not destroy significant results. It would be extremely interesting to compute perturbations around a family of variational orbits that do not do an injustice to observa-

1961AJ.....66..368R

tions, rather than for the one orbit that gives the best mathematical fit to observations. The differences in the orbits at aphelion, where the perturbations by Jupiter are largest, may be important. A true estimate needs to be made of physical uncertainties in predictions, to ensure that an adequate search is made. Periodic comets undoubtedly have been lost in the past (and are being lost at present) because of inadequate searches. It should be possible to verify results by computations by different methods, so that mistakes in computation may be discovered and corrected, as well as to compare the relative merits of different techniques. A great deal of information undoubtedly can be extracted from existing observations with vigorous and imaginative use of large-scale computing facilities now available. And in the near future precise orbit data undoubtedly will be useful in planning the direct examination of the properties of comets by means of space probes.

REFERENCES

Cunningham, L. E. 1951, *Publs. Astron. Soc. Pacific* **63**, 42, 95, 153, 209.

——. 1952, *ibid.* **64**, 35, 80, 139, 207, 320. See also *Harvard Ann. Cards*, and *I.A.U. Circ.* 1950–53.

Davidson, M. 1939, *Monthly Notices Roy. Astron. Soc.* **99**, 409.

Heckmann, O., Dieckvoss, W., and Kox, H. 1954, *Astron. J.* **59**, 143.

Kamienski, M. 1933, *Acta Astron.* (Ser. a) **3**, 1.

——. 1953, *ibid.* (Ser. c) **5**, 44.

——. 1959, *ibid.* (Ser. a) **9**, 87.

——. 1961, *ibid.* **11**, 33.

Merton, G. 1927, *Monthly Notices Roy. Astron. Soc.* **87**, 565.

van Woerkom, A. J. J. 1948, *Bull. Astron. Inst. Neth.* **10**, 445.

Whipple, F. L. 1950, *Astrophys. J.* **111**, 375.

DISCUSSION

WHIPPLE: This is a very fine work. I should like to join Miss Roemer in her plea for recalculation of some orbits. Encke's comet especially needs it, for in its early days especially the perturbations could not have been applied very accurately. Cunningham has data, but has not reduced it as yet. If I had suspected that there may be no secular changes in the period, I don't know whether I would ever have published my icy-conglomerate model! (Laughter.)

EICHHORN: If you say the accuracy limit is imposed by the *Astrographic Catalogue* (can't do better than 1″ or 2″), do you attribute this to intrinsic inaccuracy in the positions in the AG, or to proper motions, or to the uncertainty in tying the astrographic measures into a certain fundamental system?

ROEMER: It is really a combination of the quality of the reference star positions (primarily observed for the AGK1 and used without proper motions) and the long time interval involved since.

EICHHORN: Are any systematic corrections applied?

ROEMER: This is practically impossible to do, and it would probably cause damage. Let the person using the positions apply the corrections he considers desirable. Of course there is the possibility of using field plates, reduced using Yale stars or AGK2 stars, but this more than doubles the work.

——: How large are the typical cometary nuclei that you measure?

ROEMER: One practically never observes the nucleus directly. I would give very great weight to the visual observations of van den Bos, Baldet, and V. M. Slipher of the nuclei of comets close to the earth, the indicated size being from $\frac{1}{2}$ to a few km for a typical object.

HERZBERG: You mentioned an object with two nuclei. The motion with respect to each other has been measured?

ROEMER: I think one can get the velocity of separation, which gives some index of the energy of processes going on in the nuclei. This comet was at such a great distance from the sun that the disruption was not a tidal effect, but something that happened internally in the nucleus.

HERZBERG: Would you care to comment on the resemblance between comets and asteroids?

ROEMER: The Jupiter family comets cannot be distinguished from asteroids on the basis of orbits alone. When I observed Comet Arend-Rigaux on its last apparition I found that it was completely stellar on all plates. The orbit is similar to that of a minor planet, but the object was designated as a comet because it on occasion showed some diffuseness. When Baade discovered Hidalgo he was undecided whether to call it a minor planet or a comet, but he decided on the former simply because more people were observing minor planets at the time and it would be better taken care of! (Laughter.)

© American Astronomical Society • Provided by the NASA Astrophysics Data System