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ENCKE, THE COMET*

BY ZDENEK SEKANINA
Jet Propulsion Laboratory, California Institute of Technology

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ABSTRACT

The history of observations, orbital investigations, and physical studies of Encke's comet is reviewed and its significance in the quest for understanding the nature and evolution of comets is discussed. Highlighted on the background of general progress achieved are the major developments that took place over the past two centuries, such as J.F. Encke's work on the comet's anomalous orbital motion and his hypothesis of a resisting interplanetary medium; F.W. Bessel's critique of the hypothesis and his remarkable concept of recoil forces exerted on cometary nuclei; O. Backlund's arguments for apparent discontinuities in the non-gravitational perturbations of the comet's motion and the ultimate abandonment of the concept of a resisting medium; formulation of new ideas after comet theory emerged from a long period of stagnation; the vital role of Encke's comet in F.L. Whipple's icy-conglomerate model; and recent major advances in both physical and dynamical investigations of the comet, including studies of its rotation and precession, the nature of the non-gravitational anomaly, and the evolution of discrete active regions on the nucleus. Finally, prospects for future research are briefly addressed.

RÉSUMÉ

Une revue de l'histoire des observations, des mesures de l'orbite et des études physiques de la comète de Encke est présentée, ainsi qu'une discussion de son importance dans l'étude de la nature et de l'évolution des comètes. On a mis l'emphase sur les découvertes majeures des deux derniers siècles, telles que les travaux de Encke sur le mouvement orbital anormal de la comète et de son hypothèse d'un milieu interplanétaire résistant; la critique de cette hypothèse par Bessel et son concept de forces de réaction exercées sur les noyaux; les arguments de Backlund en faveur de discontinuités apparentes dans les perturbations non gravitationnelles du mouvement de la comète, résultant éventuellement à l'abandon du concept de milieu résistant; l'émergence de nouvelles idées après une période de stagnation; le rôle primordial de la comète de Encke dans le modèle du conglomérat glacé de Whipple; et les progrès réalisés dans le cadre de récentes études physiques et dynamiques de la comète, entre autres celles portant sur sa rotation et sa précession, la nature de l'anomalie non-gravitationnelle, et l'évolution des régions actives du noyau. On présente brièvement d'éventuelles avenues de recherche.

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1. Introduction. There hardly exists a serious amateur astronomer who would not know of Encke's comet. But even some amongst comet specialists may not be able to identify the object that should be called Méchain-Herschel-Pons's

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*Invited paper written on the occasion of the 200th anniversary of J.F. Encke's birth on 23 September, 1791.

comet, if the current rules for naming comets had been applied before the 1820s. Yes, of course, I am talking about the same object, whose universally adopted name is the result of recognition of J.F. Encke's remarkable work on its orbital motion. A testimony to the man's modesty is the fact that to his very death Encke had insisted on referring to this object as Pons's comet.

It took 33 years following the comet's first detection before the periodicity of its orbital motion was finally recognized. But when this hurdle was overcome, the comet presented scientists with yet another major surprise: it refused to obey the law of gravitation! And although significant advances have been made in comprehending the fine perturbations of the comet's motion, today we still are puzzled by the complicated temporal variations in these so-called *non-gravitational effects*. The experience of the past 200 years indicates that considerable knowledge of the physical behaviour of Encke's comet is required in order to understand its orbital behaviour at least to some extent. Interestingly, the first steps in this direction had been taken more than 150 years ago by Bessel (1836a, b, c), but his farsighted ideas were largely ignored in the 19th century and the first half of the 20th century. The general recognition of the physical processes involved finally arrived four decades ago in the form of Whipple's (1950, 1951) dirty-ice conglomerate model, to which Encke's comet was of critical importance. In retrospect, it is ironic that studies of the physical nature of comets were rather adversely affected by consequences of the dramatic discoveries of the 1860s that proved so beneficial to the development of a closely related discipline—meteor astronomy.

2. *History of the comet's discovery*. The story had begun more than five years before the man, after whom the comet would be named, was born. The comet was discovered by a Parisian astronomer Méchain (1786a, b) in the evening of January 17, 1786, near the star δ Aquarii as a fairly bright object with a trace of tail. The bicentennial anniversary of this event, which itself represents a milestone in the history of cometary astronomy, was unfortunately ignored, apparently because of its coincidence with the culmination of "Halleymania". Since Méchain's discovery took place merely two weeks before the comet's passage through perihelion, it is not surprising that further observations were made on only one other day, January 19, when both Messier (1789) and Méchain (1786a, b) were able to secure positional measurements just before the object's disappearance in the twilight sky. The impossibility of calculating even an approximate orbit from these observations (without restraining assumptions) probably contributed to the belated recognition of the comet's orbital periodicity.

The comet was discovered for the second time by Caroline Herschel on November 7, 1795, at Slough, England (Herschel 1796), three revolutions after Méchain's initial sighting. At the time of this telescopically made discovery the object was just visible to the naked eye according to her brother William. And although it was found independently by an amateur astronomer by the name of Carl during his visit to the Berlin Observatory on November 11 (Bode 1796) and by A. Bouvard in Paris on November 14 (Lalande 1796), Herschel is nowadays recognized as the sole discoverer at this apparition (Marsden 1989). The object was followed for three weeks by observers in England, Germany, and France. Another three revolutions later, the comet was picked up in the morning of October 20, 1805, almost simultaneously by J.-L. Pons in Marseille (von Zach 1805), by Huth (1805, 1806) in Frankfurt an der Oder, and by Bouvard (1806) in Paris. It was under observation for a whole month in France and Germany. The fourth and last discovery, four revolutions later, was made again by Pons (1818) in Marseille in the evening of November 26, 1818. The comet was observed during the second half of December and the first half of January in France, Germany, and Austria. This was the first apparition at which the comet was seen by Encke (1819; von Zach 1819), who measured its position on five occasions between January 1 and 12, 1819, at the Seeberg Observatory.

3. Early orbital studies and establishment of the periodicity.

3.1. Parabolic approximations. Using the observations by Méchain on January 17, 1786, and by Messier two days later, Burckhardt (1816) published sets of hypothetical parabolic elements for the 1786 apparition on five different assumptions regarding the comet's geocentric distance Δ at the time of the first observation: 0.2, 0.4, 0.5, 0.6, and the maximum possible, 0.942 AU. The resulting orbital elements varied within wide limits that spanned three weeks in the time of perihelion passage, almost 60° in the inclination, and nearly 0.8 AU in the perihelion distance (including a sun-grazing type of orbit). Unfortunately, Burckhardt confused the ascending node with the descending. Corrected for this error, his orbit for $\Delta = 0.6$ AU does show a degree of resemblance to the orbit of Encke's comet.

Several sets of parabolic elements were published for the comet's 1795 apparition. Their comparison by Olbers (1811) showed them mutually quite discordant except for two sets of his own. In 1805, four parabolic orbits were published, by F.W. Bessel (Olbers 1806; von Zach 1806a), by Bouvard (1806), by C.F. Gauss (von Zach 1806a), and by A.M. Legendre (von Zach 1806b). There are two interesting circumstances associated with these orbital calculations. One is that all the sets based upon the 1805 observations differed from those based upon the 1795 observations so dramatically that Olbers, who was very experienced in orbital studies, did not even consider the possibility of the two objects being identical when he discussed the 1795 orbit in 1811. The second interesting circumstance is that von Zach (1806b), commenting on Bessel's unsuccessful attempts at improving the elements, remarked that "*perhaps the orbit deviates strongly from a parabola*". Encke (1819) attributed the expression of doubt about the parabolic character of the orbit directly to Bessel. This appears to be the first suggestion of its kind in the literature and, to this author's knowledge, the only one put forth before the 1819 apparition.

The developments involving orbital determinations based upon the comet's 1818–19 positional observations were described in considerable detail – together with extensive references to historical precedents – by von Zach (1819). Encke entered the scene by calculating two sets of parabolic elements, using the method of Olbers, but with little success: the residuals showed strong systematic trends reaching 3 arcmin over a period of time from December 22, 1818, till January 12, 1819. Pons's observation on November 27, 1818, left entirely unacceptable residuals of 15 and 30 arcmin, respectively, in the comet's positions calculated from the two sets of elements. These embarrassing errors led to an anecdotal situation that implied the possibility that the culprit was Pons's observation rather than the calculated orbit. As quoted by von Zach (1819), responding to his comment that comet positions reported by Pons were only crude estimates, not precise measurements, the latter quipped dryly: "*Our parallactic instrument is a paralytic instrument, one cannot do anything well with it*", a statement showing that complaints by observers about equipment problems have by no means been confined to the second half of the 20th century. But it soon turned out that, however inaccurate Monsieur Pons's positional observations may have been, they were not off by the Moon's diameter!

3.2. Elliptical orbit. Commenting on contemporaneous studies of this comet's orbital motion, von Zach (1819) noted that the elements of this object calculated by Encke "*resemble somewhat those of the first comet of 1805*". It was apparently Encke's own line of thinking that made him abandon further attempts at fitting a parabolic orbit. Instead, he began to search for an elliptical solution.

This effort met with instant success. Encke's first elliptical solution for 1819, which indicated that the comet's orbital period was near 3.6 years, was based upon Pons's observation of November 27 (the same crude estimate referred to above), B. Nicolai's observation made at Mannheim on December 22, and Encke's own observation made at Seeberg on January 12. None of the 11 observations available to Encke at that time yielded residuals larger than 0.6 arcmin and the strong systematic trends, which showed so prominently in the parabolic solutions, were now absent (*cf.* Encke 1819). Although an improved orbit later did indicate that the position reported by Pons was off by about half an arcmin, its accuracy was not much worse than that of the positions communicated by some of the other observers. Following the identification of the comet of the year 1819 with that of 1805, Olbers (*cf.* Encke 1819, von Zach 1819) suggested first that the comet of 1795, and later that the comet observed in January 1786, were also apparitions of the same object. Encke's calculations soon confirmed these identities and led to narrowing down the uncertainty in the comet's orbital period to 1204–1207 days; that is, extremely close to 3.3 years. Together with the perihelion distance of 0.33–0.34 AU, this orbital period implies that at all times the comet stays within 4.1 AU of the Sun – well within Jupiter's orbit. It was proposed by von Zach (1819) that the comet of 1801 was yet another apparition of the same object, but this turned out not to be the case. Similarly, von Biela's (1822) suggestion of the object's identity with the second comet of 1766 was rejected by Encke (1823).

Encke's triumph reached a peak when the comet was successfully recovered at its next return to the Sun, on June 2, 1822, by Rümker (1823, 1826) during his stay at Paramatta, New South Wales, Australia. He observed the comet for three weeks and found it to follow closely an ephemeris provided by Encke (1820). For nearly two weeks in June 1822, the object was also seen by Robertson (1831) in Rio de Janeiro.

The circumstances that led to the establishment of the comet's orbital periodicity illustrate the slow and painful road of a quest for scientific knowledge. Encke deserved to have the comet named after him, because he played the key role in the endeavour and did a lion's share of the work necessary. Two other scientists that should be singled out as contributing significantly to the solution were Olbers and Bessel. To document the efforts expended, Table I lists selected sets of the comet's orbital elements for the 1786, 1795, 1805, and 1819 apparitions published in the contemporaneous literature and compares them with the best elliptical orbits that Encke was able to come up with in 1819 and with the orbits that are currently considered as the most representative.

Encke's (1819) calculation of the Jovian perturbations of the comet's motion in the period 1795–1819 and his comparison of the *true* and *perturbed* orbital elements in the three apparitions brought the first phase of his investigations to a close. One of his conclusions, stating that the average orbital period decreased from 1207.9 days between 1795 and 1805 to 1207.3 days between 1805 and 1819 after the planet's perturbations were accounted for, may be regarded as the starting point of the second phase of the orbital studies—the investigation of deviations from the gravitational law.

4. *Determination of the non-gravitational perturbations.*

4.1. Encke's investigations. In the years following 1819, Encke's suspicion that the comet's orbital motion could not be explained solely by accounting for planetary perturbations was repeatedly confirmed. First, his improved solutions that included Jupiter's perturbations only yielded the average corrected orbital periods of 1208.11 days between 1786 and 1795, 1207.88 days between 1795 and 1805, and 1207.42 days between 1805 and 1819. The incorporation of the effects by the planets Mercury to Saturn (Encke 1820) then led to the following averages: 1208.22 days between 1786 and 1795, 1207.77 days between 1795 and 1805, and 1207.25 days between 1805 and 1819. These results indicated a systematic *acceleration* of the comet at a rate of approximately 0.1 day per revolution per each revolution about the Sun. When the presence of the acceleration was again confirmed by the observations made in 1822, Encke (1823) concluded that the comet's motion was apparently influenced by a resisting interplanetary medium.

For the reader who is not intimately familiar with the fundamental laws of dynamics, a notion of an orbital *acceleration* being caused by a *resisting* medium may appear to be contradictory. However, a simple calculation shows that this indeed is so. The virial theorem yields the following expression for the orbital velocity V as a function of the orbit's semi-major axis a and heliocentric distance r,

$$V^2 = (2\pi\gamma)^2 \left(\frac{2}{r} - \frac{1}{a}\right), \tag{1}$$

where γ is a constant. If r and a are in AU (astronomical units) and V in AU yr^{-1}, then $\gamma = 1$ AU$^{3/2}$ yr^{-1}. Kepler's third law relates the semi-major axis to the orbital period P:

$$a^3 = \gamma^2 P^2. \tag{2}$$

Thus, a change of dV in the orbital velocity at a given heliocentric distance r is given by

$$2VdV = \left(\frac{2\pi\gamma}{a}\right)^2 da = \frac{8\pi^2 P}{3}\left(\frac{\gamma}{a}\right)^4 dP, \tag{3}$$

or

$$dP = \frac{3P^{5/3}V}{4\pi^2\gamma^{4/3}} dV. \tag{4}$$

Since the coefficient at dV is positive, dP has the same sign as dV. For a resisting medium, $dV < 0$ and therefore also $dP < 0$: the orbital period becomes shorter with time and the comet's motion is observed to be accelerated. The reason for this is that a decrease in the velocity results in an orbit of smaller dimensions, analogous to the effect of atmospheric drag on an Earth's artificial satellite. This effect more than offsets the object's actual slowdown. From equation (4) one can calculate the change in the orbital velocity that is equivalent to the observed change in the orbital period. For example, at perihelion – when the comet's orbital velocity reaches 70 km/s – a non-gravitational effect of 0.1 day in the period corresponds to a velocity decrease of only 0.16 m/s. It turns out that of

TABLE I

COMPARISON OF SETS OF THE ORBITAL ELEMENTS DERIVED FOR THE 1786, 1795, 1805, AND 1819 APPARITIONS OF ENCKE'S COMET (EQUINOX 1950.0)

Time of perihelion passage (UT)	Argument of perihelion	Longitude of ascending node	Orbital inclination	Perihelion distance (AU)	Orbital eccentricity	Author(s) and reference(s)
			Apparition 1786			
	°	°	°			
Jan. 28.35	167.74	329.63	13.55	0.427	1.0	Burckhardt (1816)[a]
Jan. 31.37	182.47	336.45	13.62	0.33483	0.84836	Encke (1819)
Jan. 31.360	182.202	336.469	13.687	0.33603	0.84842	Marsden and Sekanina (1974)
			Apparition 1795			
Dec. 15.292	164.147	3.271	24.728	0.21506	1.0	Prosperin (1796; Olbers 1811)
Dec. 15.528	164.423	1.354	24.299	0.22662	1.0	von Zach (1796; Olbers 1811)
Dec. 16.146	174.22	345.56	20.07	0.258	1.0	Bouvard (Olbers 1811)
Dec. 15.905	179.094	343.439	21.773	0.24521	1.0	Olbers (1811)
Dec. 15.870	177.901	344.153	21.954	0.24401	1.0	Olbers (1811)
Dec. 15.888	168.558	353.936	21.784	0.24454	1.0	Encke (1819; von Zach 1819)
Dec. 21.941	182.006	336.845	13.728	0.33442	0.84888	Encke (1819)
Dec. 21.963	182.258	336.448	13.690	0.33549	0.84859	Marsden and Sekanina (1974)
			Apparition 1805			
Nov. 18.631	163.226	346.656	15.629	0.37862	1.0	Bessel (Olbers 1806)
Nov. 18.541	163.641	347.132	15.896	0.37624	1.0	Bouvard (1806)
Nov. 18.216	177.086	342.220	17.585	0.34649	1.0	Gauss (von Zach 1806a)
Nov. 18.511	163.884	347.147	15.989	0.37566	1.0	Legendre (von Zach 1806b)
Nov. 18.602	162.878	347.093	15.689	0.37867	1.0	Encke (1819)
Nov. 22.000	182.428	336.385	13.577	0.34042	0.84618	Encke (1819)
Nov. 21.986	182.316	336.445	13.587	0.34065	0.84653	Marsden and Sekanina (1974)

TABLE I (*Concluded*)

Time of perihelion passage (UT)	Argument of perihelion	Longitude of ascending node	Orbital inclination	Perihelion distance (AU)	Orbital eccentricity	Author(s) and reference(s)
			Apparition 1819			
Jan. 25.402	174.991	331.234	14.693	0.35310	1.0	Encke (von Zach 1819)
Jan. 25.465	175.330	333.205	15.211	0.32962	1.0	Encke (1819; von Zach 1819)
Jan. 25.457	175.766	330.932	14.811	0.35256	1.0	Nicollet (1820)
Jan. 27.746	182.348	336.578	13.661	0.33398	0.84909	Encke (1819)
Jan. 27.754	182.422	336.397	13.637	0.33509	0.84863	Marsden and Sekanina (1974)

[a] Best of five hypothetical orbits calculated from two positions as a function of geocentric distance Δ at the time of Méchain's observation on Jan. 17, 1786, (for $\Delta = 0.6$ AU). The longitude of the ascending node has been corrected by 180°. It has been assumed that the time of perihelion passage was given by Burckhardt in Paris mean time.

the orbital elements the time is by far the most sensitive to the non-gravitational perturbations of the motion.

In order to account for this non-gravitational anomaly in his orbital calculations, Encke (1823) assumed that the spatial density of the resisting medium varied inversely as the square of heliocentric distance and that the impeding force U exerted on the comet varied as the medium's density and as the square of the comet's orbital velocity:

$$U = U_0 \left(\frac{V}{r}\right)^2, \tag{5}$$

where U_0 is a constant, to be determined from the observations. Encke calculated that the effects of the force on the comet's mean motion (which he used instead of the period P) and on the orbital eccentricity varied, respectively, as V^3/r^2 and $-V/r^3$, that their ratio was independent of U_0, and that the force had a negligible effect on the position of the line of apsides and none on the orbit plane's position in space.

The results of Encke's lifelong work on the comet's orbital motion are included in eight massive volumes (Encke 1829, 1831, 1833, 1842, 1844, 1851, 1854, 1859) and in a large number of less extensive papers. A major obstacle that frustrated Encke throughout his work was the fact that the masses of the perturbing planets were poorly known in his time. Even though the non-gravitational effect was much too large to be explained in its entirety by errors in the planets' masses, the latter introduced a degree of inherent uncertainty in the orbital solutions and especially in the derived non-gravitational parameters. The resulting errors in the calculated planetary perturbations appear to have contributed to large positional residuals in the normal places (sometimes reaching 1 arcmin or more) and to ubiquitous systematic trends in their distribution. In fact, Encke considered it necessary to carry out some of his calculations twice, on two different assumptions regarding the mass of Jupiter. Also annoying was the lack of a good estimate for the mass of Mercury, with which the comet had recurring encounters near its perihelion. In his early studies, Encke adopted for the Sun-to-Mercury mass ratio the Laplacean value of $M_\odot/M_☿ \approx 2{,}000{,}000$, much too low by a factor of 3(!) compared with the best determination that is nowadays available from Mariner 10 measurements of the planet's gravity field, $M_\odot/M_☿ = 6{,}023{,}600 \pm 250$, (Anderson *et al.* 1987). Later, Encke attempted to calculate Mercury's mass by solving for its correction along with the corrections to the orbital elements and to the non-gravitational parameter in a differential least-squares procedure. In this manner he obtained very inconsistent values for the planet's mass, ranging from $M_\odot/M_☿$ of ~3,200,000, which was determined from the orbital runs 1819–1838 and 1819–1848, to ~8,200,000, which was established from an 1828–1848 run terminated at perihelion in 1848, and to ~10,300,000, which was derived from a run that covered the same apparitions but included the 1848 post-perihelion observations. It is noted that on November 22, 1848, or 4 days before perihelion, the comet passed by Mercury at a record minimum miss distance of 0.039 AU.

In one of his last major papers on the subject, Encke (1858) was able to link all the comet's apparitions between 1819 and 1848 – with tentative extensions through 1858 – on the assumption of a temporally invariable resisting medium, the only disturbing circumstances having been large residuals of the normal places and their unsatisfactory temporal distribution. Until the time of his death in 1865, Encke did not apparently have the slightest doubts about the correctness of his model for the resisting interplanetary medium. Yet, in desperate attempts by Encke's followers to salvage at least some features of his hypothesis, the concept was soon to undergo major revisions, eventually to be abandoned in its entirety.

4.2. Investigations by von Asten, Backlund, and the Russian School. Encke's death effectively terminated the work on the comet's motion that had been conducted in Berlin, although a search ephemeris for the apparition of 1868 was prepared there by Becker and von Asten (1868). In 1870 the centre of activity moved to the Pulkovo Observatory, near St. Petersburg, Russia, when von Asten joined its staff and began his systematic orbital investigation of Encke's comet. He first calculated the perturbations by the planets for the period of 1848–1875 and subsequently made an attempt to link the comet's apparitions 1819–1875, employing Encke's hypothesis of the resisting medium as well as his extensive calculations of the perturbations by the planets between 1819 and 1848. To improve the formal representation of the normal places for the apparitions 1819–1868, von Asten (1872, 1878) included the masses of Mercury, Earth, and Jupiter in the differential-correction procedure, which, in addition to the six orbital elements, also incorporated two parameters that characterized the non-gravitational effects in the mean motion and in the orbital eccentricity. Unfortunately, the best fit that he was able to achieve required that the masses for both Earth-Moon and Jupiter systems be assigned, by today's standards, entirely inadmissible values, namely, $M_{\odot}/M_{♁} \approx 306{,}000$ (fully 7 per cent less than the true ratio) and $M_{\odot}/M_{♃} \approx 1049.6$ (instead of 1047.4). In spite of this arbitrary, unrealistic approach, von Asten was unable to link the 1819–1868 apparitions with the comet's return of 1871, when the embarrassingly large residuals of his orbital solution reached ~24 arcmin! The only "explanation" that he was able to come up with was an artificial, *ad hoc* hypothesis that the orbit must have been gravitationally altered following the comet's extremely close encounter with an undiscovered asteroid.

The concept of the resisting medium was strongly defended by von Asten. The argument that he considered most convincing was based on the fact that the ratio of the non-gravitational effect in the mean motion to that in the eccentricity derived from the least-squares solution agreed almost perfectly (and certainly within the errors involved) with the ratio required by Encke's hypothesis.

After von Asten's untimely death in 1878, the orbital investigation of Encke's comet was continued by O. Backlund, who arrived at the Pulkovo Observatory in 1879. His first priority was to examine why von Asten was unable to accommodate the apparitions of 1871 and 1875 with the pre-1871 apparitions. In his study of the comet's motion in the period 1871–1881, Backlund (1884) showed that von Asten's unsatisfactory results were brought about by a sharp decrease in the acceleration of the comet's motion before 1871. He re-examined the issue of the dependence of the impeding force of the resisting medium upon the comet's orbital velocity and heliocentric distance, assumed it in the general form

$$U = U_0 \frac{V^m}{r^n}, \tag{6}$$

and showed that the observed relation between the non-gravitational contributions to the mean motion and the orbital eccentricity is satisfied by any positive values of m and n such that $2 \leq m + n < +\infty$, a condition that is satisfied by Encke's solution ($m = n = 2$).

Backlund considered it highly desirable that the comet's perturbations by the planets Mercury through Saturn be recalculated for the whole period starting from 1819, covering 22 revolutions about the Sun. With the help of a staff of assistants, he was able to complete this immense task in several years and the results were subsequently published in six volumes (Backlund 1892, 1893a, b, 1894a, b, 1898). Using this information, Backlund (1894c) showed that it was impossible to combine the apparitions 1819–1891 into a single run assuming a constant value for the parameter U_0 in Eq. (6). Instead, he divided the whole interval into three periods, 1819–1858, 1858–1871, and 1871–1891, and found that the acceleration diminished in 1858 and again in 1868 but that it was constant before 1858 and again after 1871. Backlund solved for the mass of Mercury as one of the unknown parameters in the equations of condition and obtained $M_\odot/M_☿ \approx 9{,}697{,}000$ and 9,745,000, respectively, from the 1819–1858 and 1871–1891 runs. This agreement convinced him of the correctness of his result and he used $M_\odot/M_☿ = 9{,}700{,}000$ in all of his subsequent investigations.

The comet's motion between 1891 and 1908 was analyzed in another set of papers (Backlund 1908, 1909, 1911a) and the results revealed several disturbing facts (*cf.* also Backlund 1910). First of all, Backlund experienced major difficulties with accommodating in his solutions the apparitions at which the comet was observed only after perihelion, a problem that had also vexed Encke and von Asten. For example, a run based upon three pre-perihelion apparitions, 1895, 1901, and 1905, left unacceptable residuals of 0.5 arcmin and 4.2 arcmin, respectively, in the normal places of the post-perihelion apparitions 1898 and 1908. The rate of acceleration was found to decrease again about the time of perihelion in 1895. On January 9, 1905, 3 days before its perihelion passage, the comet approached Mercury to 0.056 AU, the closest encounter since 1848. In order to fit the normal place in 1908, Backlund considered two options: either to increase the mass of Mercury by about 50 per cent (which would have been the decision in the right direction), or to assume that the acceleration decreased once again about the time of perihelion in 1905. Unfortunately, he chose the second option.

By that time, Backlund realized that Encke's hypothesis of the resisting medium was in deep trouble. In 1910 he wrote: "*The cause of the acceleration of the mean motion cannot be a resisting medium of so simple a nature as Encke supposed* ...". Backlund considered electric forces, especially because he believed that the abrupt changes in the rate of acceleration seemingly coincided with the times of maxima of the solar activity, even though he admitted that the number of the events was too small to be statistically significant. He therefore saw no alternative but to modify Encke's hypothesis to make it more acceptable in the light of his new results. Backlund found that in addition to the condition of $m + n \geq 2$ for the exponents in the expression (6) for the impeding force, a second condition was implied by the fact that the perturbations arising from the resisting medium could not be higher than the first order, which required that

$$0 \leq m + 2n - 1 \leq 1. \tag{7}$$

Since the resistance must depend upon the comet's velocity, he reasoned, it follows that the integer value of m must be 2 (to avoid n becoming negative) and that therefore $n = 0$; thus the density of the medium is independent of heliocentric distance. Backlund (1910) concluded that all the conditions and observational constraints were satisfied only if the acceleration was caused by the comet's brief encounter with "*a meteoric swarm in the neighbourhood of perihelion*". The decrease in the rate of acceleration was explained by him as an indication of a decrease in the spatial density of particles in the encountered meteor ring or swarm.

Following his work on the apparitions 1891–1908, two additional studies were published by Backlund (1911b, 1915), one each on the apparitions of 1911 and 1914. The solution for the apparitions 1904–1914 required a further drop in the comet's acceleration, whose rate was now less than 40 per cent of the value for the apparitions 1819–1858.

Backlund passed away in 1916. In recognition of his major contributions to the understanding of the comet's motion, the Russian Academy of Sciences decided that in the Academy's future publications the comet be referred to as Encke–Backlund's comet. It should be pointed out, however, that this renaming has never been advocated or upheld outside Russia (and later the Soviet Union). While Backlund's work was held in high esteem world-wide, as exemplified by the Gold Medal of the Royal Astronomical Society that he was awarded in 1910, the comet has always been referred to as Encke's comet in the West.

Although neither von Asten nor Backlund were Russian by birth, it apparently was Backlund's legacy that led a number of Russian astronomers to dedicate significant shares of their scientific careers to the continuation of the orbital work on this object. Backlund's influence has also been apparent in the style and the methodology employed by the members of this Russian School. The comet's apparitions 1918–1934 were analyzed by Matkiewicz (1935) and the apparitions 1924–1934 by Idelson (1935a, b), who used some of Matkiewicz's perturbation calculations. The unsatisfactory results of both investigations had been puzzling until Makover (1955) noticed a conceptual error in one of the formulae used by Matkiewicz. The quality of the orbital work improved considerably when Makover and his collaborators at the Institute for Theoretical Astronomy entered the scene. By this time the hypothesis of the resisting medium was finally put to rest thanks to orbital investigations on other periodic comets, such as Recht's (1939) finding that the motion of d'Arrest's comet had long been subjected to a definite deceleration, an effect that Encke's hypothesis could not explain. It is, however, unfortunate that Makover and his collaborators introduced no conceptual innovations in their mathematical approach to reflect the new understanding of the non-gravitational forces. A modification that they did incorporate in the equations was rather a dubious one, aimed at simplifying the calculations: the non-gravitational effect was assumed to have the character of an instantaneous impulse at each perihelion passage (reminiscent in fact of Backlund's meteor ring). In the first paper, dealing with the apparitions 1937–1951, Makover (1955) showed that by then the comet's acceleration decreased to only about 20 per cent of its 1819–1858 value. This result was essentially confirmed by Luchich (1958), who found a slightly higher acceleration for the apparitions 1931–1937 and 1931–1947. Acceptable values for the mass of Mercury were found by Makover (1956) from the run 1937–1954 and by Makover and Bokhan (1961) from the run 1898–1911. These authors also essentially confirmed the value for the comet's acceleration that Backlund (1910, 1911a) found from his orbital solution for the apparitions 1895–1905. Further investigations that used the virtually identical method were undertaken by Makover and Luchich (1963) for the apparitions 1947–1957 and by Kastel (1971) for the apparitions 1954–1964, and by Bokhan and Chertenenko (1973), who linked the comet's returns between 1901 and 1971 in ten three-apparition runs (*cf.* also Marsden 1974).

A qualitatively new approach to the non-gravitational orbit determination was initiated in the late 1960s. These developments were preceded and stimulated by significant advances in the understanding of the physical nature of comets and their activity in general and by new ideas on the structure and composition of cometary nuclei in particular. The achieved progress, as it applies to Encke's comet, is reviewed next.

5. *The non-gravitational forces and the comet's activity.* By cometary standards, the orbit of Encke's comet is very stable, both in dimensions and in its orientation in space. This is the result of the small aphelion distance (Section 3.2), which prevents encounters with Jupiter at miss distances smaller than ~0.9 AU. Because of an approximate commensurability of 7:2 between the comet's and Jupiter's orbital periods, however, moderately close encounters have a tendency to recur every 23 years, although deviations from the *exact* resonance cause this pattern to break down at times (a ratio of 18:5 expresses the reality better). Whipple (1940) devised an ingenious approximate method of accounting for Jupiter's long-term effect on the comet's orbit by assuming that the entire perturbation occurs at the point of aphelion. His results were subsequently confirmed by Brouwer's (1947) rigorous calculation of the secular perturbations. The net effects are an oscillatory variation in the comet's inclination relative to the ecliptic between 4° and 16° recurring every 3,400 years and a slow counterclockwise rotation of the line of apsides, at a rate of about $0\overset{\circ}{.}7$ per century, accompanied by a rotational motion of the nodal line of twice the period of the inclination cycle. There is no systematic effect from Jupiter on the comet's mean motion. On time scales of a century or less, these changes in the angular elements are sufficiently small that they do not affect the basic pattern for the comet's observability near perihelion by terrestrial observers. This pattern is determined by the time of the year the comet transits the perihelion point: when the passage occurs between mid-September and the end of January, the comet is observable before perihelion from the northern hemisphere; when it takes place between late April and early August, the comet is visible after perihelion from the southern hemisphere. Mixed patterns are possible for the other perihelion times – from February till mid-April or from mid-August through early September – but these configurations almost invariably represent rather unfavourable returns. The closest approaches to Earth (0.2 to 0.3 AU) occur when the perihelion takes place in December or in the second half of May. These are the most favourable pre-perihelion and post-perihelion apparitions, respectively.

The highly uneven observing conditions at the comet's various returns to the Sun are bound of course to have a profound effect on the amount and the quality of the data that are gathered at each apparition. While all types of ground-based observations are affected (with a notable exception of those that can be made in broad daylight, such as the various radio and some infrared experiments), unfavourable observing circumstances take the heaviest toll of the physical observations, which are hardly ever made under even slightly adverse conditions.

5.1. The first fifty years of physical observations (1786–1835). At the early apparitions of Encke's comet, the attention of observers was directed primarily toward positional measurements. The object's appearance – if not ignored – was described in only crude qualitative terms. Besides the brightness, discussed separately in Section 5.7, limited information was sometimes provided on the dimensions of the coma or the nucleus condensation, on the possible presence of a tail or another kind of extension, and – unfortunately only quite rarely – on the coma morphology, which has recently become of major interest in studies of the physical processes on the nucleus.

Of the nine apparitions observed in the first fifty years following the comet's discovery by Méchain, six were of the pre-perihelion/northern-hemisphere type (1786, 1795, 1805, 1819, 1825, and 1829) and two were of the post-perihelion/southern-hemisphere type (1822, 1832); the last one (1835) was of the mixed type, although observations were made only before perihelion from the northern hemisphere.

The reports by Méchain (1786a, b) and by Messier (1789) on the comet's appearance on January 17–19, 1786, are contradictory as to the visibility of a tail. Messier remarked that the comet was fairly well defined, more perceptible than the nearby cluster M2 in the constellation of Aquarius, and with a bright nucleus enveloped in the nebulosity. During the 1795 apparition, Herschel (1796), Bode (1796) and Olbers (1796) independently agreed that the object was round, ill-defined, and without a distinct nucleus. By contrast, in 1805 the comet appears to have been much brighter. Huth (1805, 1806) remarked that on October 20, 1805, it rivalled the nebula M31 in the constellation of Andromeda in size, hue, and brightness, except that it was nearly circular and more sharply terminated at its northern boundary than elsewhere. Five days later it was brighter and it broadened perceptibly on its sunward side, toward the south-southeast. This appears to be the first account of the comet's asymmetric, sunward-extended coma, noticed at most (but not all) apparitions ever since. On October 29 Huth saw a nucleus located at the northern boundary of the coma and on November 1 he commented on a tail 3° long, equivalent to a projected length of 4.5 million km. At about the same time a tail was also reported by Olbers (1806) and by Bode (1806).

In 1818–19 the comet was described as a small, ill-defined, and shapeless nebulosity at the time of discovery (Pons 1818a), as round or slightly oval during December 1818 (Pons 1818b), and as matching the appearance of the cluster M2 in early January 1819 (Encke 1819). The comet was a difficult telescopic object in 1822 when observed by Rümker (1823, 1826) after perihelion. In 1825 it was consistently reported to be round, centrally condensed, but with no distinct nucleus (Cacciatore 1825, 1826, Plana 1825, Encke 1826, Schwerd 1826). The next apparition was a favourable one and the comet was observed extensively by Struve (1829) at Dorpat (now Tartu) with the 23-cm refractor, then the largest in the world. Until the end of October 1828 the comet's centre was the brightest point in the coma. However, one week later the nucleus condensation was near the anti-solar boundary of the enormous, slightly elongated nebulosity, estimated at 400,000 km in diameter. The brightest part, located distinctly off-centre, was about 90,000 km across. The northern boundary was fairly sharp and parabolically curved, while the coma was gradually fading away on its south side. Similar descriptions were offered by Struve from his observations during the following several weeks, except that the comet's overall dimensions were diminishing. Olbers (1829; see also Schur and Stichtenoth 1899), who observed the comet on a number of occasions in November and early December, commented on its botryoidal (*traubenähnlich*) outlines on December 1, likewise implying an asymmetric coma of the kind mentioned by Struve at the same apparition and by Huth in 1805. No physical observations were made at the apparitions of 1832 and 1835.

Perhaps the most valuable pieces of information available from the first fifty years of physical observations of Encke's comet are the drawings by Huth (1806) and by Struve (1829). Reproduced in figure 1, they represent authentic evidence that is essential for studies of temporal variations in the comet's activity patterns, thus assisting in the reconstruction of the probable evolution of the comet's nucleus over a period of nearly two centuries.

5.2. Bessel's investigations. In the first half of the 19th century, F.W. Bessel appears to have been the only vocal critic of the hypothesis of the resisting medium. He was the first (Bessel 1836a) to draw a parallel between the discrepancy of several days between the observed perihelion passage of Halley's comet and Rosenberger's (1835, 1836) otherwise accurate prediction on the one hand and the accelerated motion of Encke's comet on the other hand. A suggestion of this kind was bound to be controversial, because the probability was high that the discrepancy for Halley's comet was due to errors of observation at the comet's earlier apparitions (upon which the prediction for 1835/36 was necessarily based) and due to uncertainties in accounting for the planetary perturbations over the long periods of time involved. Regardless of the circumstances surrounding Rosenberger's calculations, it is a fact that the motion of Halley's comet has recently been shown to be indeed affected by a non-gravitational deceleration whose rate is nearly constant at $\sim$4 days per revolution per revolution (Michielsen 1968, Kiang 1972).

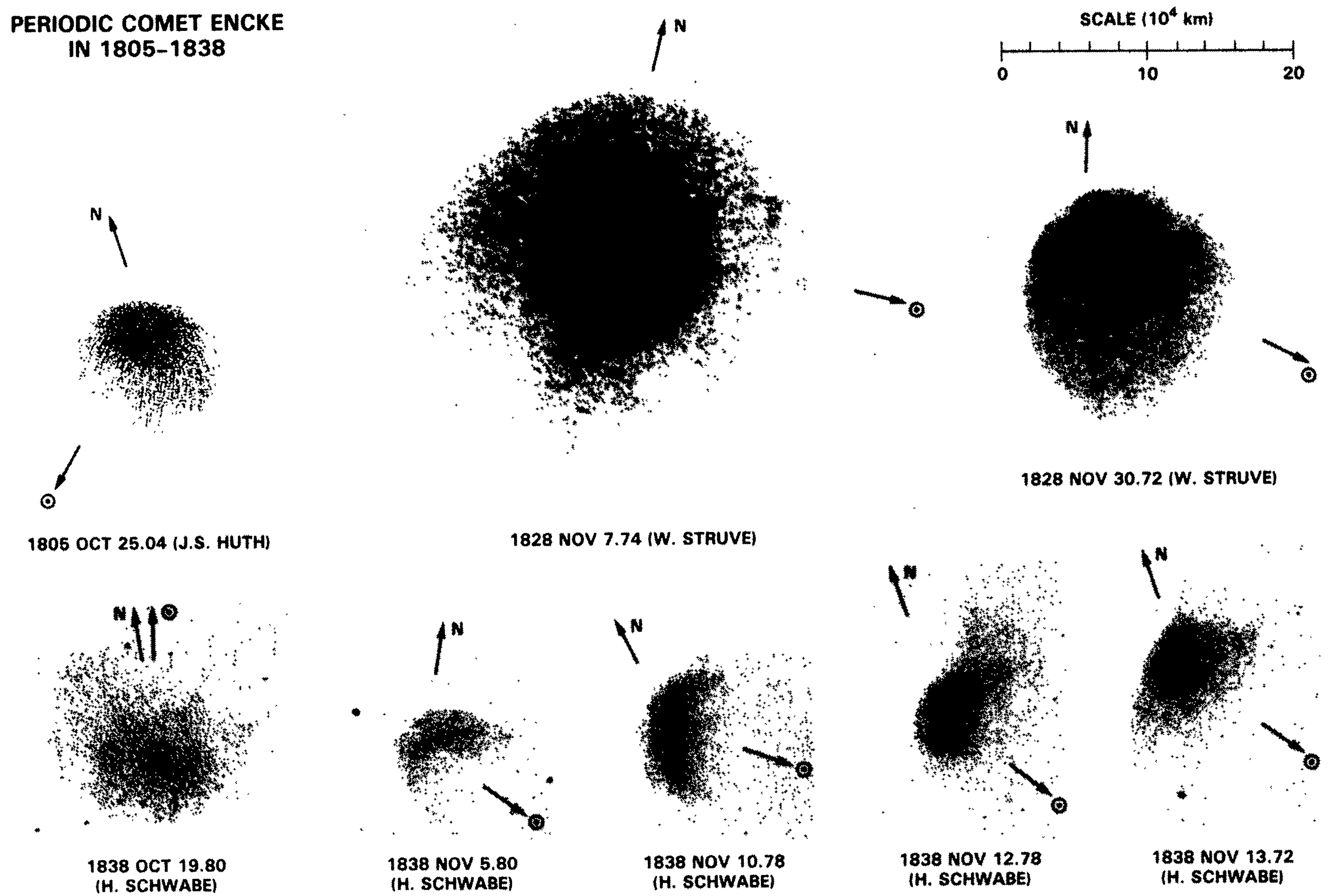


FIG. 1—The earliest drawings of the fan-shaped coma of Encke's comet, made by J.S. Huth (1806) at Frankfurt an der Oder in October 1805, by W. Struve at Dorpat (now Tartu) in November 1828, and by H. Schwabe (1839) at Dessau in October–November 1838. The drawings have been reduced to a common linear scale. The directions to the north (N) and to the Sun (⊙) are indicated. The times of observations are UT.

Bessel (1836a) pointed out that it was only the acceleration of Encke's comet, not its *cause*, that was clearly demonstrated. He complained that effects of the resisting medium had never been detected in the motions of planets and the Moon and that no other phenomenon was known to require its existence. Bessel's (1836b) extensive observations of Halley's comet in October 1835, about the time of its closest approach to Earth, convinced him of the presence near the comet's nucleus of emanations of matter spewn preferentially in the sunward direction. His physical insight led Bessel (1836c) to conclude that effects of the recoil forces that are exerted on the nucleus (as dictated by the conservation of momentum law) by the mass ejected asymmetrically with respect to perihelion should bring about a non-gravitational perturbation of the comet's orbital motion. He showed that the semi-major axis should be decreased (and the comet accelerated), if the comet is more active before perihelion and *vice versa*, and that for mass-loss rates that he considered reasonable the effect should be large enough to be readily detectable by observation. Bessel was also quick to notice that, unlike the recoil mechanism, the hypothesis of the resisting medium would fail to explain the motion of a comet either affected by no acceleration or subjected to a deceleration. Bessel concluded, however, that the controversy could not readily be settled by quantitative arguments because both hypotheses (recoil and resisting medium) depended upon physical parameters whose values could not be ascertained. He obviously recognized the weakness of his earlier argument that implied the deceleration of Halley's comet and there was no other periodic comet known at the time whose orbital motion was studied well enough to prove the correctness of his hypothesis.

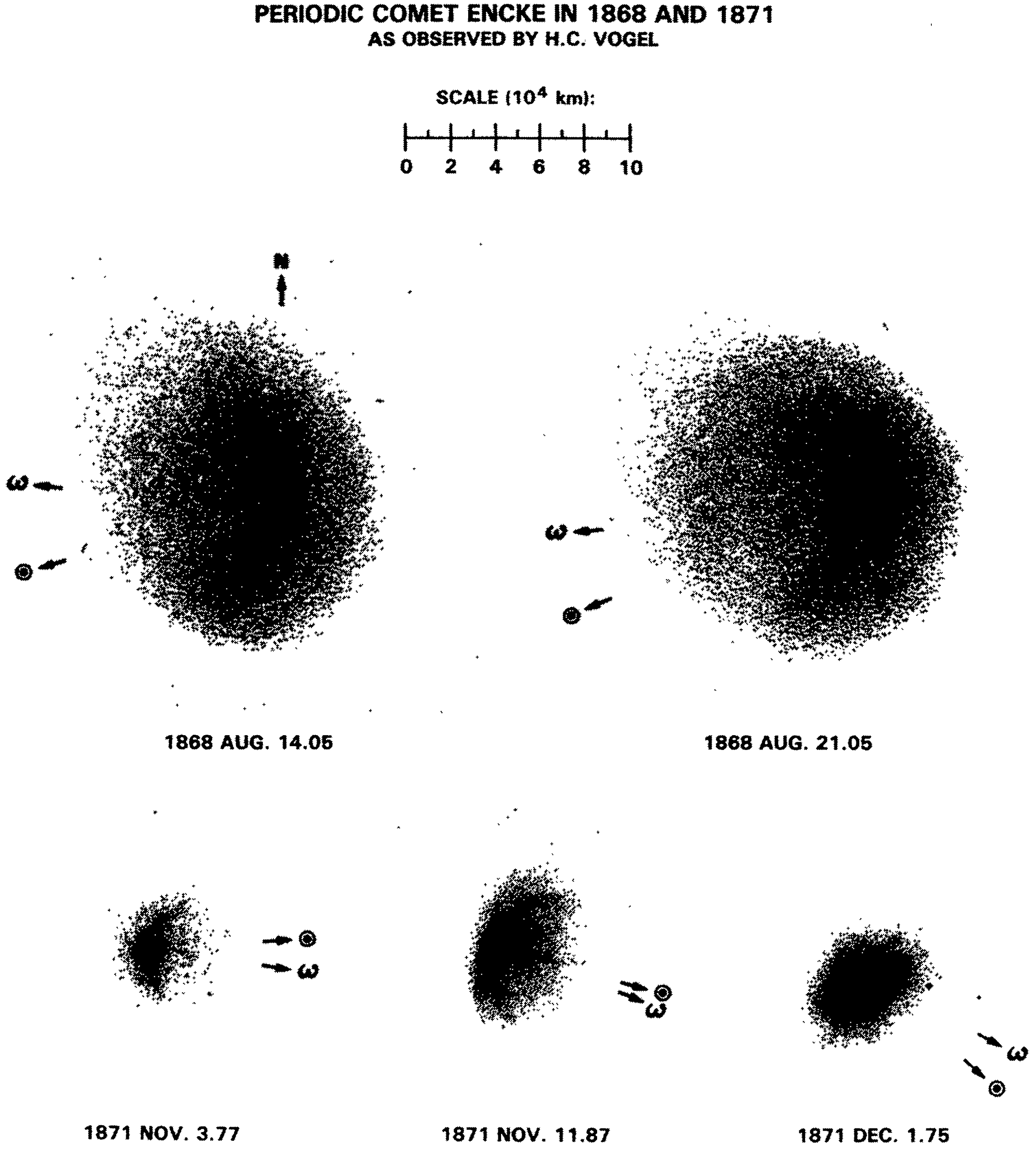
5.3. Comets and meteor streams: the great confusion. In retrospect, the critical issue behind the controversy involving Encke's and Bessel's concepts was a fundamental difference in their perception of the nature of a cometary nucleus. Bessel's scepticism about the existence of any resisting medium was based upon his belief that every comet had a solid nucleus and that therefore the absence of effects of such a medium in the motions of the planets made their presence in the motions of comets unlikely and rendered the medium's existence highly doubtful. Encke had been aware of this potentially lethal weakness long before it was pointed out by Bessel. Referring to Olbers for a statement of support and to Herschel for observational evidence, Encke (1823) argued that the density of comets is so low that it may be compared to that of the zodiacal light. He maintained that what holds for the solid, high-density planets does not apply to comets. Encke, like so many others in his time, did not distinguish between the nucleus and the coma of a comet.

It is regrettable that the perception of comets as some kind of particle clouds was strongly reinforced by the developments in the 1860s, when newly discovered comets (that included Thatcher 1861 I, Swift-Tuttle 1862 III, and Tempel-Tuttle 1866 I) were found to move about the Sun in orbits that were identical with those of known meteor streams (e.g., Schiaparelli 1867, Peters 1867, Weiss 1867, d'Arrest 1867, Galle 1867). In the ensuing meteor euphoria, the recognized relationship between comets and meteor streams was unfortunately misinterpreted and portrayed almost universally to mean that comets *are* meteor streams. And so it happened that the era of great advances in meteor astronomy also became an era of great confusion in cometary astronomy. It took comet science almost a whole century to recover from this conceptual blunder. In the meantime, the hypothesis of the resisting medium kept surviving in one form or another (Section 4.2) even though its plausibility already was in serious doubt.

5.4. Augmenting the database in the era of visual observing (1838–1891). While comet theory made hardly any progress for a hundred or so years following Bessel's far-sighted ideas of the 1830s, the time was not wasted entirely. As the size of telescopes grew and the quality of the optics improved, observers began to pay greater attention to detail, showing more interest in the apparent morphology of cometary heads (jets, fans, halos, streamers, and other near-nucleus features). This interest is documented by a large number of reports by outstanding observers of the mid- and late 19th century, including W.C. and G.P. Bond, J.F.J. Schmidt, A. Secchi, and A. Winnecke.

The 1838 apparition of Encke's comet was one of its most favourable on record. The comet approached Earth to within 0.22 AU in early November 1838 and remained within 0.9 AU for nearly three months. Extensive physical observations were made by Encke and J.G. Galle (Encke 1840), by Challis and J.W.L. Glaisher (Challis 1840), and by Schwabe (1839), who also published a series of drawings (figure 1). The comet's appearance was repeatedly depicted as fan-shaped, with the nucleus condensation located on the anti-sunward side, at the apex of the fan. However, in 1842 the comet was consistently described by several observers as perfectly circular and brightest at its centre (Laugier and Mauvais 1842, Airy 1844, Challis 1845). Following an unfavourable apparition of 1845, the sunward fan was detected again in 1848 (e.g., Bond 1849, 1851, Schmidt 1849, Wichmann 1849). While the reports from 1852 are generally inconclusive, the comet was observed as a nearly circular nebulosity after perihelion in 1855 (Maclear 1863).

During the rest of the 19th century, the comet's fan-like appearance was observed time and again. It is not possible to list here all the reports, but at least a brief mention should be made of the notable observations by Winnecke (1862) and by Tietjen (1863) during the 1861/62 apparition, by Schmidt (1862, 1868, 1872, 1882) during the 1861/62, 1868, 1871, and 1881 apparitions, and by Vogel (Bruhns 1868, Vogel 1871, 1872) in 1868 and 1871. Vogel's drawings of the comet, reproduced in figure 2, as well as those made by Carpenter (1872)



1868 AUG. 14.05

1868 AUG. 21.05

1871 NOV. 3.77

1871 NOV. 11.87

1871 DEC. 1.75

FIG. 2—Fan-shaped coma of Encke's comet on drawings made by H.C. Vogel at Leipzig in August 1868 and at Bothkamp in November–December 1871. The drawings have been reduced to a common linear scale. North (N) is up, the east to the left. The directions to the Sun (⊙) and the calculated orientations of the comet's projected spin vector (ω) are indicated. The times of observation are UT. (Reproduced from Sekanina 1988a.)

and by Key (1872) in 1871 and by W.H. Robinson (Stone 1892) in 1891 all show the sunward fan most convincingly. By the end of the 19th century it was recognized that Encke's comet was developing the sunward fan along the *inbound* leg of the orbit at virtually every apparition, while no coma structure was ever observed *after* perihelion. The only exception in the second half of the 19th century was the apparition of 1875 when the comet was reported to be an essentially round object both before and after perihelion (Bruhns 1875, von Konkoly 1875, White 1875). In spite of the ubiquitous reports on the fan's presence, however, its significance – beyond attesting to the material's sunward ejection – was not recognized until recently (Sections 5.8 and 6).

The 1870s marked the beginning of the comet's spectroscopic observations. The visual spectrum was found to be dominated by three emission bands now known to belong to the Swan system of $C_2(\Delta v = -1, 0, +1)$, of which the middle was usually described as the brightest (e.g., Vogel 1871, 1872, Tietjen 1873, von Konkoly 1875, Trépied 1885). The continuum was invariably reported as absent or barely detectable.

5.5. Introducing new observing techniques (1894–present). A new era in the exploration of Encke's comet was begun with its photographic recovery by Wolf (1894) on October 31, 1894. While most positional and physical observations were still made visually at that time, the photographic technique contributed a significant fraction of the data less than two decades later. The first low-dispersion photographic spectra were obtained at the 1914 apparition (Tikhov 1925) and even though the response of the plates used was shifted appreciably to the blue region of the spectrum relative to that of the eye, the comet's photographic appearance was found to be consistent with its visual appearance. In particular, the development of the sunward fan along the pre-perihelion arc of the orbit was repeatedly confirmed photographically and the comet's images on the plates showed much resemblance to the drawings available from the earlier apparitions.

In 1907 began the remarkable career of G. Van Biesbroeck, one of the most prolific comet observers of all time, who observed first visually at the Uccle Observatory, later both visually and photographically at the Yerkes Observatory, photographically at the McDonald Observatory, and – in his final years – photographically at several sites in the Tucson area, including the Kitt Peak National Observatory and the Catalina Station of the University of Arizona's Lunar and Planetary Laboratory. Although positional measurements were Van Biesbroeck's primary objective, he distinguished himself from most of his peers by annotating his reports with detailed descriptions of each comet's physical appearance. He almost certainly set a record by observing Encke's comet at 11 apparitions between 1917 and 1961 (see Van Biesbroeck references 1920–1962). He contributed a lion's share of information on the comet's sunward fan that was used in recent nucleus investigations (Sections 5.8 and 6). Examples of the comet's photographic images taken by Van Biesbroeck in 1924, 1928, and 1937 are displayed in figure 3. Like the drawings in figures 1 and 2, the photographic

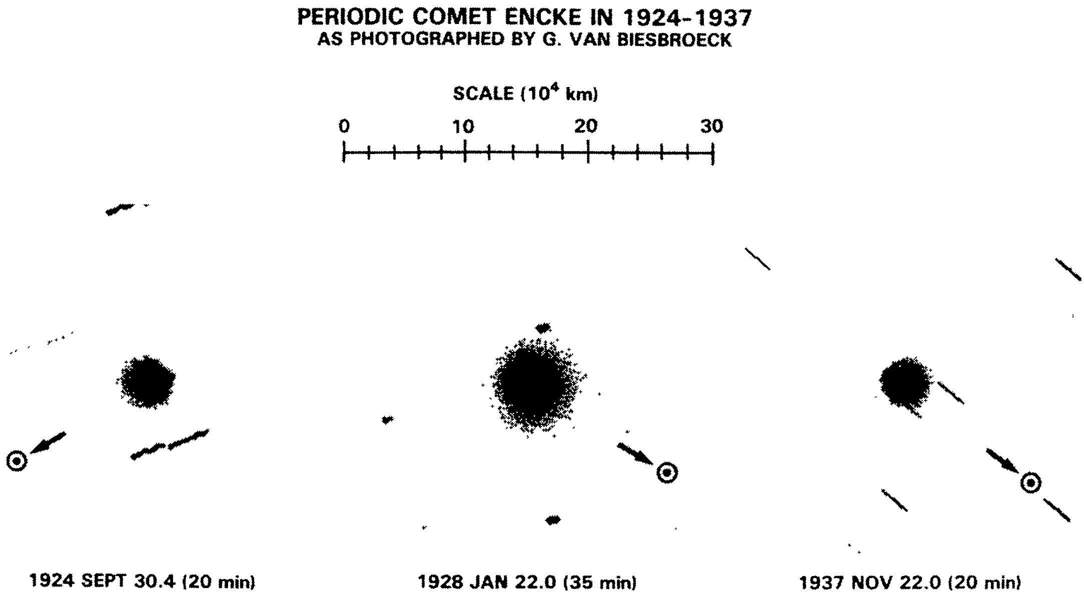


FIG. 3—Fan-shaped coma of Encke's comet on photographs taken by G. Van Biesbroeck with the 61 cm $f/4$ reflector of the Yerkes Observatory. The 1924 image was exposed on a Graflex plate, the 1928 image on a Speedway plate, and the 1937 image on an Ortho press plate. The images have been reduced to a common linear scale. North is up, the east to the left. The directions to the Sun (☉) are indicated. The times of observation are UT and the exposure times are given in parentheses. (Original plates courtesy of Yerkes Observatory; the figure is adapted from Sekanina 1988b.)

images provide evidence on both the prominence of the fan and the deviations of its axial direction from that of the Sun and the temporal variations in the cone angle. Also worth noting are Van Biesbröeck's (1944) observations at the apparition of 1941 that indicate the absence of the pre-perihelion fan, a situation reminiscent of those in 1842 and 1875 (Sec. 5.4).

The 20th century has witnessed major advances in the construction of large reflecting telescopes. An apparent image of Encke's comet on a photograph obtained by F.G. Pease with the 152-cm reflector at Mount Wilson on September 2, 1913 – when the comet was near its *aphelion* – prompted Barnard (1914) to suggest that with large reflecting telescopes the comet should be observable photographically throughout its orbit, a feat that has been achieved with hardly any difficulty in the past 20 years (e.g., Roemer 1972). In fact, following its return to perihelion in 1971, Encke's comet has never again been assigned a preliminary letter identification, since it really is no longer recovered upon its approach to the Sun. Instead, together with periodic comets Schwassmann–Wachmann 1 and Gunn, it has been classed as one of the "annual" comets (Marsden 1973). An excellent example of the superior resolution and the high imaging quality achiev-

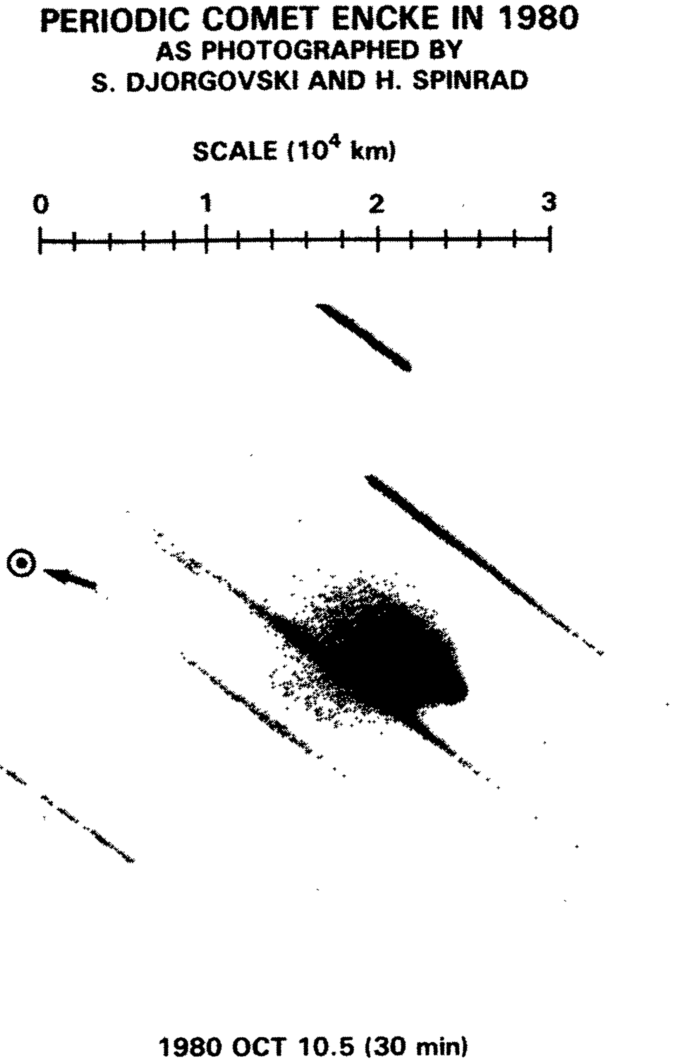


FIG. 4—Fan-shaped coma of Encke's comet on a photograph taken by S. Djorgovski and H. Spinrad with the 400 cm *f*/3 reflector of the Kitt Peak National Observatory in 1980, employing a IIIa-J emulsion and a GG385 filter. North is up, the east to the left. The direction to the Sun (⊙) is indicated. The time of observation is UT and the exposure time is given in parentheses. (Print courtesy of H. Spinrad; the figure is adapted from Sekanina 1988b.)

able nowadays with a large-aperture telescope and a modern type of emulsion is a photograph of Encke's comet exposed by Djorgovski and Spinrad (1985) with the 400-cm reflector at the Kitt Peak National Observatory on October 10, 1980, which is reproduced in figure 4. The introduction of charge-coupled device (CCD) arrays as detectors on large reflecting telescopes has substantially facilitated imaging of Encke's comet near aphelion in the optical spectrum even with the use of broad-band filters. As a result, campaigns of intensive monitoring of the comet at large heliocentric distances have successfully been conducted during the past decade (e.g., Barker, Cochran, and Rybski 1981, Jewitt and Meech 1987, Luu and Jewitt 1990).

The role of experienced amateur observers has grown steadily during the 20th century. Today they participate in monitoring both the orbital motion of Encke's comet by providing astrometric observations and its physical behaviour by supplying information on its brightness and appearance. Among the most interesting observations are those of a sunward tail *after* perihelion, by Jones (1985) in February 1961 and by Pearce (1984) in April 1984, which are found to refer to a fan-like phenomenon of the same kind that the comet has for so long been known to display only before perihelion. It therefore appears that we are confronted here with an entirely new development, which is different from the *anti-tail* phenomenon that the comet occasionally exhibits for a limited time after perihelion (Sekanina and Schuster 1978).

In addition to the CCDs, other innovative observing techniques were recently introduced that have much enhanced the flow of information on the comet's physical properties. Broad-band photoelectric photometry and spectrophotometry were first applied to Encke's comet in 1957 (Mianes 1958, Liller 1958), followed by narrow-band photometry of the molecular species in the optical spectrum as appropriate interference filters became available (see A'Hearn, Millis and Thompson 1983 for a review). In 1970 the comet was observed for the first time from space in the vacuum ultraviolet: using a photometer on board the *Orbiting Geophysical Observatory* OGO-5, Bertaux, Blamont and Festou (1973) detected the Lyman Alpha emission of the hydrogen cloud that surrounded the nucleus to a distance of more than half a million km. Since 1980, numerous observations of the OH emission near 308.5 nm have been made with a camera on board the *International Ultraviolet Explorer* (IUE), complementing the difficult ground-based observations (A'Hearn, Millis and Thompson 1983, A'Hearn *et al.* 1985). In addition, far-ultraviolet spectra have been obtained with the IUE's spectrographs since 1980 (Weaver *et al.* 1981. Feldman, Weaver and Festou 1984) and, in mid-May 1984, a sunward fan of the kind previously observed from the ground by Jones and by Pearce was detected with the IUE's Fine-Error Sensor (A'Hearn *et al.* 1985; see also Sekanina 1988b). Last but not least, in mid-April 1984, the comet's Lyman Alpha emission was detected from aboard the Pioneer Venus spacecraft (Combi, Stewart, and Smyth 1984). In the meantime, ground-based observations of Encke's comet were extended into the near and thermal infrared beginning in April 1974, when Ney (1974) measured fluxes in four broad bands, centred on the wavelengths of 2.2, 3.5, 4.8, and 8.5 μm. The comet's first infrared spectrophotometric observations, in the 3–4 μm region, were made in 1987 (Gehrz *et al.* 1989). Finally, both passive and active experiments were recently conducted in the microwave region. A radio detection of the comet's OH emission at 18 cm (1667 and 1665 MHz) was attempted unsuccessfully near perihelion in 1977 (Despois *et al.* 1981) but a positive observation was made in late December 1980 after additional unsuccessful attempts at the 1980 apparition (Bockelée-Morvan *et al.* 1981). And in early November 1980, Kamoun *et al.* (1982) succeeded in marginally detecting echoes from the comet's nucleus using the S-band (12.6 cm wavelength) system of the large dish at the Arecibo Observatory.

5.6. Whipple's model of a dirty-ice conglomerate nucleus. Whipple's (1950, 1951) comet model marks the beginning of an era of major achievements in cometary research. The model was developed on careful considerations of the various constraints on the physical conditions under which comets could have formed and evolved. Whipple argued for their origin in a cold environment, demanded by the need for preserving large amounts of chemically stable hydrogen-based ices – including a high abundance of water ice – that become volatile at room temperatures. He was convinced that the molecular species observed in the optical spectra of comets are derived from parent volatile substances that are frozen in the nucleus and, upon approach to the Sun, released by sublimation in the near-vacuum environment. The ices are mixed in the nucleus, envisaged as a discrete mass, with a matrix of refractive materials to constitute a genuine conglomerate. Whipple's profound expertise in meteor physics allowed him to predict comet properties consistent with observed evidence from shower meteors – samples of cometary debris. He concluded that comets should possess little structural strength and maintained that sublimation of ices should leave behind a layer of poorly cemented aggregates of refractory material that would greatly reduce the rate of heat transfer into the nucleus interior. Whipple contemplated that grains of meteoric material that are smaller than a critical size would be carried away from the nucleus by momentum transfer from the sublimating ices and proposed that nucleus rotation and heat-transfer lags determine the preferential direction of the outgassing. The non-gravitational effect in the mean motion is generated in this model by the momentum's transverse component exerted on the rotating nucleus; if this component of the momentum points in the general direction of the orbital motion (a prograde rotation), the comet is decelerated, and *vice versa.* The observed non-gravitational perturbations rendered it possible for Whipple to calculate the mass-loss rate, which for Encke's comet – the primary object of his interest – came out to be a significant fraction of one per cent of the comet's mass per revolution. These results led him to typical estimates of several kilometres for the radii of cometary nuclei.

Even from this extremely brief description of Whipple's model one can immediately notice the difference between his and Bessel's interpretations of the non-gravitational anomaly: because of the involvement of nucleus rotation, the effect arises from a *non-radial* component of the recoil force in Whipple's concept, while Bessel assumed that the force was applied in the *radial* direction and the effect was attributed by him to the force's asymmetric action with respect to perihelion. Interestingly, the relative magnitudes of these two contributions are still debated at the present time.

It should also be pointed out that an independent explanation of the non-gravitational effects was offered by Dubiago (1948). Based on his study of five comets, including Encke's, he found that the momentum from gaseous species observed in the optical spectra of comets was insufficient to produce an anomaly of the observed magnitude and concluded that the momentum should arise from the expulsion of dust. Although a mechanism has recently been proposed for dust ejection not involving sublimating ices, it can operate only at large heliocentric distances and affects grains of very small (sub-micrometre) dimensions. Thus, dust generally fails to transfer any significant momentum to the nucleus upon its ejection, and Dubiago's paradigm, lacking a plausible mechanism, does not represent a viable alternative to Whipple's model.

5.7. The light curve and the production of water. Few brightness estimates are available for Encke's comet from the late 18th century and the first half of the 19th century. The best data from this period of time are probably those based on comparisons of the comet's brightness with that of nearby stars or, better yet, extended sources such as nebulae or globular clusters. The first such comparison was made by Messier (1789), who reported the comet to be more conspicuous than the cluster M2 on January 19, 1786 (Section 5.1). This indicates that the comet was brighter than visual magnitude 6.5 at the time. Unfortunately, Messier did not say how much brighter the comet was. Huth (1805, 1806) was more specific, when he compared the comet's brightness to that of M31 on October 20, 1805 (visual magnitude 3.5). Less than one month later, Olbers (1806) reported the comet to be of magnitude 4. At subsequent apparitions, it was repeatedly estimated at magnitude 5 several weeks before perihelion, but in 1842 R. Main (Airy 1844) found the comet to appear "*exactly like a star of the 3rd magnitude*" when detected in strong daylight only a few days before its perihelion passage. All these estimates are unfortunately subject to great uncertainties, because no standardized magnitude scale had been in existence before 1856, when the Pogson scale was proposed, and because observers had no experience whatsoever with assessing the brightness of extended objects. It is also noted that the first 16 apparitions of Encke's comet predated F.W.A. Argelander's *Bonner Durchmusterung* (published in 1859–1862), which provided at least crude brightness estimates for the catalogued stars.

The situation improved in the second half of the 19th century, when visual photometry became more popular and comet observers stood up to the challenges that the brightness determination of comets presented. Pioneering this field of comet science were J.F.J. Schmidt, E.E. Barnard, and J. Holetschek, among others. In the late 19th century and the early 20th century, useful compilations of the physical characteristics of Encke's comet, with primary emphasis on the brightness, were published successively by Berberich (1888), by Deichmüller (1893), and by Holetschek (1905, 1916).

Van Biesbroeck, already mentioned in Section 5.5, contributed a large number of comet Encke's brightness estimates in the 20th century. However, he often used more than one instrument, and sometimes observed the comet both visually and photographically on the same night, and it is not always clear from his accounts what kind of magnitude was given. More homogeneous sets of magnitudes were obtained by career visual observers, especially Beyer (1938, 1950, 1955, 1962, 1972) whose observations spanned five apparitions between 1937 and 1971, and two others who are still active: Jones (1951, 1954, 1979, 1980, 1984, 1985, 1987, 1988) with observations at six apparitions between 1951 and 1987 and Bortle (1980, 1981, 1982, 1984, 1990, 1991), also at six apparitions between 1967 and 1990.

In estimating the total brightness of a comet, the critical issues of properly accounting for instrumental effects (telescope aperture, reflector versus refractor, photographic versus visual, etc.), for differences in the magnitude scales among the observers, and for effects of varying observing conditions (low altitude above the horizon, small elongations from the Sun, etc.) have never been answered to complete satisfaction. Because of these uncertainties, the problem of long-term variations in the intrinsic brightness of Encke's comet has remained controversial. The proponents of a slow rate of fading ($\sim$1 magnitude per century or less) point to the fact that the comet's brightness in the 20th century has been underestimated, especially when determined photographically, and that magnitudes by experienced visual observers at recent apparitions have not confirmed the fading rates derived from less selective data sets (Kresák 1965; Kresák and Kresáková 1990). On the other hand, one can argue that a steeper rate of fading ($\sim$2 magnitudes per century or more) is supported by comparisons of the comet's light curve at recent apparitions with the brightest estimates from the early 19th century and by the highly probable circumstance that today's visual observers account much more completely for the contribution from the faint, outer regions of the coma to the object's integrated brightness, while estimates by the 19th century observers generally referred only to the nucleus condensation or the inner coma.

In any case, however, from its first recovery by Rümker in 1822 (Section 3.2) until quite recently, it appeared that Encke's comet was always much fainter intrinsically after perihelion than before it. Although this is exactly what Bessel's hypothesis requires for a comet's orbital motion to be accelerated, this fact kept escaping the attention of many generations of comet astronomers and physicists.

For example, Backlund (1910) called attention to this brightness asymmetry of Encke's comet when discussing the results of his calculations on the comet's motion, but he tried – in vain, of course – to explain the anomaly in terms of the orbital geometry and never considered abandoning the concept of a resisting medium. It is only now that Kamél (1991) finds from his examination of the comet's light curve that the brightness anomaly has all but disappeared. This conclusion is confirmed in figure 5 that I compiled from more than 350 magnitude estimates made by 37 selected visual observers between 1918 and 1987. The figure shows that in the 1980s, the comet's post-perihelion fading was indeed much less steep than it had been in the 1950s, the 1960s, and even the early 1970s, and that the light-curve's peak was shifting from the pre-perihelion arc of the orbit in 1951–1954 to its post-perihelion arc in 1984–1987. In fact, this most recent light curve exhibits an excess brightness outbound up to ~13 days from perihelion, while the opposite is true at larger heliocentric distances. Beyond ~25 days from perihelion, the inbound and the outbound branches run approximately parallel to each other, separated by some 0.6 magnitude on the average, out to at least 40 days from perihelion. In addition, the figure contrasts the relative stability of the light curve's inbound branch in the decades before 1950 with its changing shape more recently. And, also corroborating Kamél's results, the figure indicates that Encke's comet has recently been growing brighter, especially near and after perihelion. Thus, the comet's fading has by no means been monotonic. Periods of modest brightening do of course dramatically reduce the *average* rate of fading over long spans of time.

Historically, the visual light curve has been a convenient measure of the activity of Encke's comet. When it became apparent that the radicals optically identified in cometary spectra are derived by photodissociation from more complex parent species (e.g., Bobrovnikoff 1942, Wurm 1943, Swings 1948) that have no transitions at visible wavelengths and, especially, when Whipple (1950) suggested that water ice could be a major constituent of cometary nuclei, the question arose whether the visual light curve – to which neither water nor its dissociation products contribute materially – is at all representative of the total gas (or water) production from comets. Since the continuous spectrum (hence, the contribution from fine dust) is all but non-existent in Encke's comet (except at larger heliocentric distances, see Newburn and Spinrad 1985), the relative production rates of water and of the species radiating in the optical spectrum (primarily C_2) have become of particular interest. There was a need for the development of new techniques to determine the production levels of the various species observed and to compare their temporal variations with the light curve. The first step in this sustained effort was Haser's (1957) model for exponentially decaying molecules in a parent–daughter scenario. This theory provides a relationship among the column density of a radical, its production rate and ex-

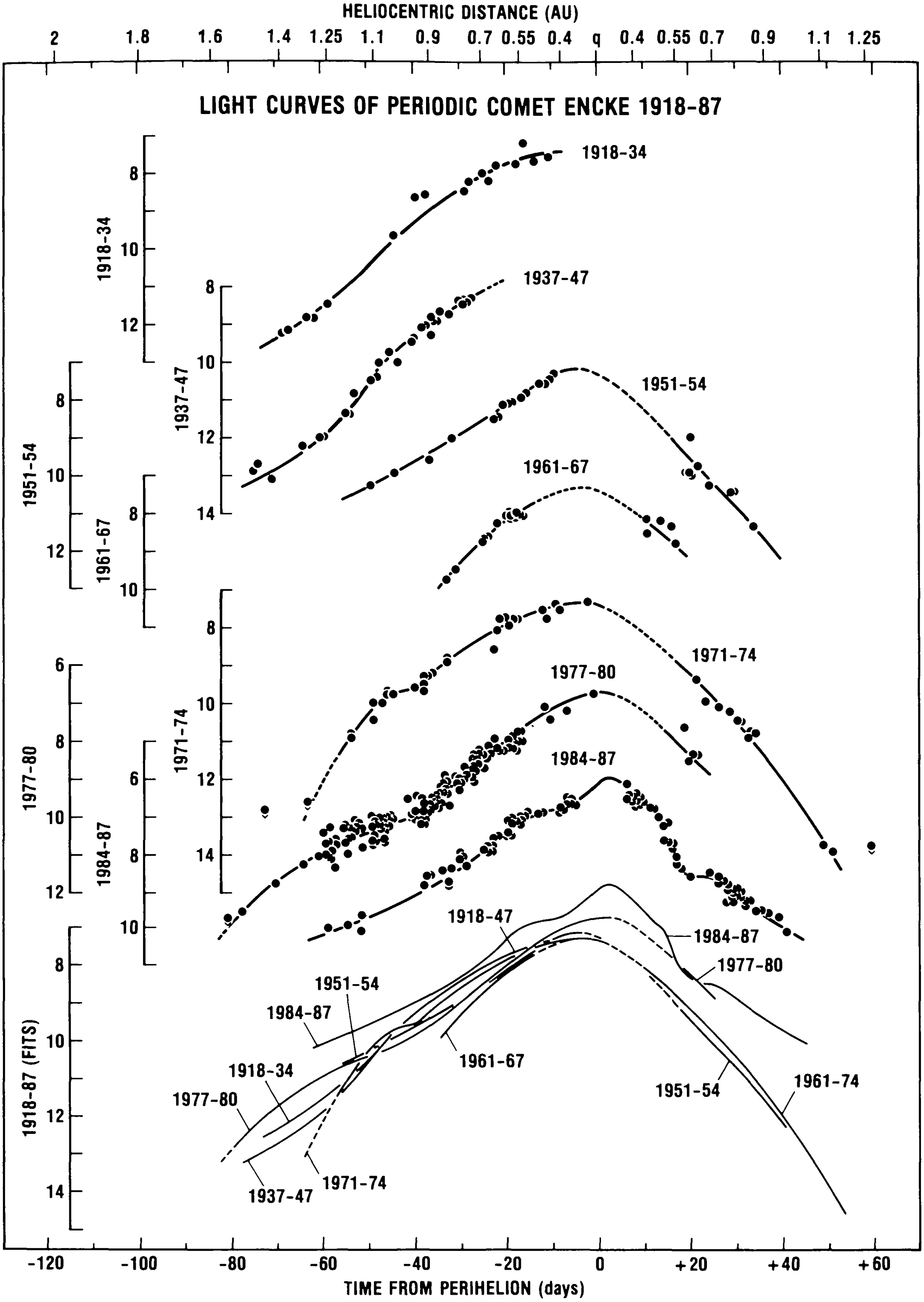


FIG. 5—Visual light curves of Encke's comet at the apparitions 1918–1987. The brightness estimates were normalized to 1 AU from Earth and to a standard magnitude scale. Inverted carets indicate that the data points are upper limits (non-detections). The bottom panel compares the seven fitted light curves to show the long-term variations. (Reproduced from Sekanina 1991.)

pansion velocity, and the scale lengths of both the radical and the parent species (see also Newburn and Spinrad 1984). The column density is derived from the observed monochromatic flux in one or more spectral bands of the radical, if its emission rate, or g-factor, is known. Although more sophisticated models have since been proposed [e.g., Festou's (1981) vectorial model for the dissociation of water], Haser's paradigm still enjoys considerable popularity today.

The neutral water molecule has no transitions in the optical spectrum. And, as in other low-activity comets, the vibrational transition of water in the near infrared (at 2.66 μm, which cannot be observed from the ground because of water vapour in the Earth's atmosphere) and the rotational $6_{1,6} - 5_{2,3}$ transition in the microwave spectrum (near 1.35 cm) have not yet been detected in Encke's comet. Instead, information available on the comet's production of water relies at present entirely upon the abundance measurements of its photodissociation products: OH, O, and H. The bulk of the data available comes from observations of the 0–0, 1–1, and 1–0 bands of the $A^2\Sigma^+ - X^2\Pi$ transition of the hydroxyl in the near ultraviolet at, respectively, 308.5, 314.4 and 282.5 nm, while the balance of the data is from observations of the forbidden line of atomic oxygen at 630.0 nm (the brighter line of the $^1D - ^3P$ red doublet), the Lyman Alpha line of atomic hydrogen in the vacuum ultraviolet at 121.6 nm, and the Λ-doublet transition of the hydroxyl at the radio wavelengths near 18 cm. Comparisons with the optically identified species have indicated that the productions of C_2 and CN in Encke's comet are typically two or three orders of magnitude lower than the water production and that the production of C_3 is lower by an additional factor of about ten (A'Hearn *et al.* 1985).

The composite water-production curve of Encke's comet, based upon the data accumulated from the 1971 and 1980–1987 apparitions, is exhibited in figure 6. Its shape differs dramatically from the shape of the visual light curve before the 1970s, but less so from that at recent apparitions. In 1980, A'Hearn, Millis, and Thompson (1983) detected a sudden drop in the production rate of water about four weeks before perihelion. However, this anomaly was less apparent in 1984, which prompted A'Hearn *et al.* (1985) to suggest that the time of the drop varies from apparition to apparition. Also, a gross disparity between the magnitudes of the Greenstein effect before and after perihelion was reported by A'Hearn and Schleicher (1988) from their analysis of high-dispersion spectra of Encke's comet taken with the IUE in 1980 and 1987. From the intensity distribution in the 0–0 band of the OH population in the coma they found a residual sunward radial velocity of about 1.6 km/s before perihelion in 1980 but only 0.3 km/s after perihelion in 1987 at about the same heliocentric distance. These results obviously refer to the systematic velocity component of the parent (water) molecules at the time of their dissociation, not at sublimation. The fairly large errors involved do not allow one to argue convincingly about perihelion asymmetry in the outgassing momentum, but A'Hearn and Schlei-

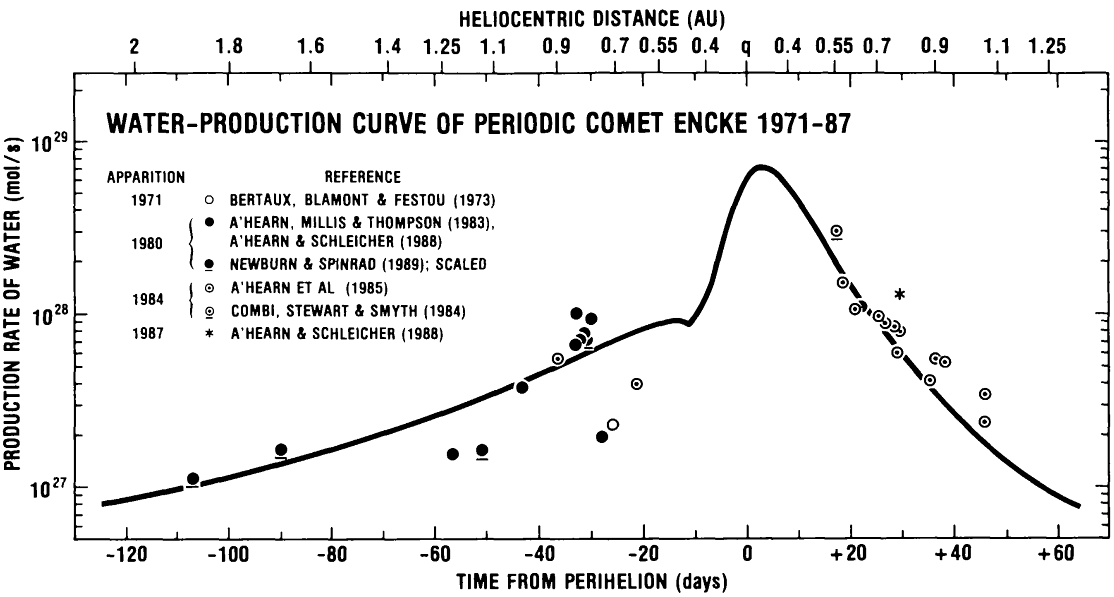


FIG. 6—Production curve of water for Encke's comet at the apparitions of 1971 and 1980–1987. The results by A'Hearn, Millis, and Thompson (1983), by A'Hearn *et al.* (1985), and by A'Hearn and Schleicher (1988) are based on their near UV observations of OH; those by Newburn and Spinrad (1989), on the forbidden line of oxygen [OI]; and those by Bertaux, Blamont, and Festou (1973) and by Combi, Stewart, and Smyth (1984), on observations of the Lyman Alpha line of HI. The solid curve is a rotation-averaged production curve of water calculated from the two-source model. (Reproduced from Sekanina 1991.)

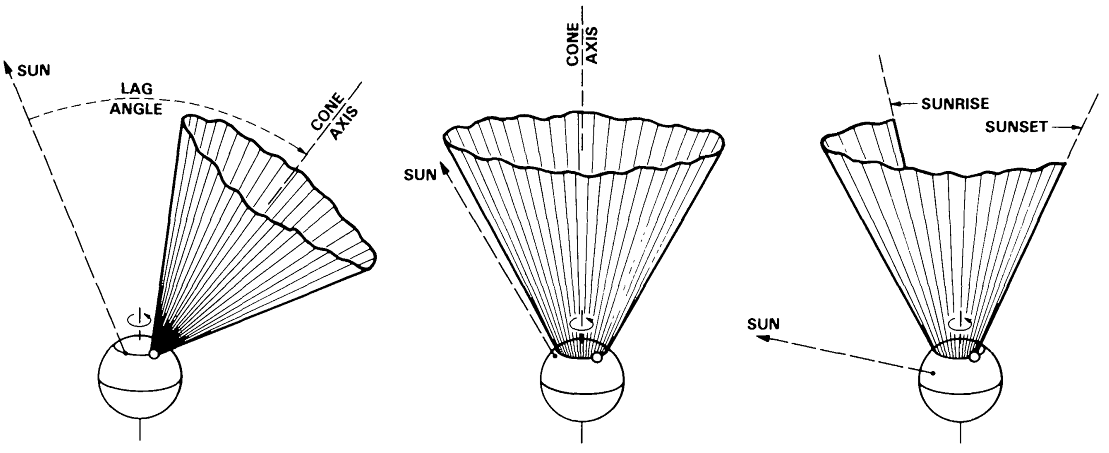
cher's conclusion that the direction of the observed pre-perihelion outflow must have essentially coincided with the sunward direction to avoid unrealistically high expansion velocities is reasonable. The issues of temporal variations in the comet's gas production and molecular velocities are of critical importance to the investigations of the nucleus rotation and precession, as described below.

5.8. Nucleus: rotation, precession, dimensions, and discrete sources of activity. The first determination of the rotation period of Encke's comet was based upon Whipple's halo method (Whipple and Sekanina 1979, Whipple 1982), which yielded a value of 6^h33^m at 1900 and a spin-up rate of $\sim 21^m$ per century. However, this result was not confirmed photometrically by Jewitt and Meech (1987) and by Luu and Jewitt (1990) from the comet's short-term brightness variations at large heliocentric distances observed in the red region of the spectrum. Jewitt and Meech found the most probable rotation period to be $22^h26^m \pm 5^m$ in 1985–1986, when the comet was 3.1 – 4.1 AU from the Sun (near- and post-aphelion). On the other hand, Luu and Jewitt preferred a rotation period of $15^h5^m \pm 5^m$ from their photometry in 1988, when the comet was at a heliocentric distance of 3.8 AU (pre-aphelion). The observed amplitudes of the light curves were found to be ≥ 0.8 magnitude in 1985, ≥ 0.4 magnitude in 1986, and 0.62 ± 0.04 magnitude in 1988. In each case the brightness variations were assumed to have arisen from the rotation-modulated projected cross-sectional area of the aspherical nucleus; that is, the light curves were assumed to have two minima and two maxima per period. The possibility that the brightness variations were a result of the comet's rotation-modulated transient activity – which would imply rotation periods one half of those mentioned – was rejected by both Jewitt and Meech and by Luu and Jewitt, primarily because the comet's images appeared to be perfectly stellar within the seeing constraints. However, Barker, Cochran, and Rybski (1981), who observed the comet in 1979 at a heliocentric distance of 3.8 AU (post-aphelion), commented on a 1.1 magnitude outburst during which the object's appearance also remained entirely stellar. In addition, there is a problem with the brightness amplitudes. By coincidence, the comet's positions in the sky at the times of Jewitt and Meech's observation in 1985 and Luu and Jewitt's observation in 1988 were identical within a few degrees. Therefore, *regardless* of the spin-axis orientation of the comet's nucleus in space, its brightness amplitude – if due to varying cross-sectional area – should have essentially been the same for both observing runs, *unless* the nucleus precessed significantly between 1985 and 1988. Luu and Jewitt admit that a 40° precession in the three years is required to account for the amplitude discrepancy. A precessional motion of this magnitude is inconsistent with other observational evidence (see below) and a contribution from rotation-modulated activity appears to be a logical explanation of the anomaly.

The first determination of the orientation of the spin axis of Encke's comet was based upon a simple, highly-idealized model of the persistent sunward fan (Sections 5.1, 5.4, and 5.5). This feature was perceived as a projection onto the plane of the sky of expanding ejecta, emerging from the point of maximum activity (Sekanina 1979). The location of this point was assumed to be on the circle of subsolar latitude and lagging behind the subsolar point due to thermal inertia of the sublimation process. The axis of the fan was then assumed to coincide with the direction of maximum outgassing and dust emission. In this concept the nucleus was regarded as an essentially homogeneous snowball, on which the sublimation is controlled primarily by insolation. Such a premise is unacceptable for heterogeneous nuclei, on which the point of maximum emission is, in general, no longer located on the latitude of the subsolar point (Sekanina 1981). In addition, to preserve the concept of thermal lags, it was necessary to assume that activity peaked rather sharply in the afternoon, the emission fan thus representing a highly transient phenomenon on a rotating nucleus, in apparent conflict with numerous observations.

The insolation-control paradigm for the sunward fan was incorporated into a forced-precession model for Encke's comet (Whipple and Sekanina 1979), which provided an interpretation of the temporal variations in the comet's non-gravitational perturbations between 1786 and the 1970s as a product of torques exerted by anisotropic outgassing on an *oblate* spheroidal nucleus. This was a pioneering work that called attention to asphericity of comet nuclei and to the plausibility of their precession – a phenomenon whose existence is now undisputed. However, since subsequent observations indicated that comet nuclei are neither spheres nor oblate spheroids rotating about the axis of maximum moment of inertia, it became desirable that the precession model be refined and possibly overhauled. Objections were also expressed by A'Hearn *et al.* (1985) with regard to the approximation used for the recoil force (based upon the visual light curve rather than the water production curve) and by Jewitt and Meech (1987) and by Luu and Jewitt (1990) because of discrepancies between their observations and expectations based on the model's spin-vector parameters. Even though the problem with the production law could be by-passed by assuming a temporally variable efficiency of the momentum transferred to the nucleus by outflowing gas (Sekanina 1986), the insolation-control concept could no longer be defended when it became apparent that the prevailing outgassing mode of most (if not all) short-period comets is emission from sunlit, highly isolated sources that make up only a small fraction of the nucleus surface.

Four years ago I proposed an alternative conceptual model for the persistent sunward fans of comets, based on the assumption that the ejecta flow from a discrete source on the nucleus is *highly collimated* (Sekanina 1987). This restriction should apply primarily to dust ejecta, whose motions are, by and large, highly organized and diagnostic of the location of the parent source on the nucleus surface. Although little is known about dust in Encke's comet, evidence from thermal infrared observations (Gehrz *et al.* 1989) supported by the existence of both a prominent dust trail (e.g., Sykes *et al.* 1986) and the associated meteor stream (Whipple 1940, Whipple and Hamid 1952) indicates that large particles are important. If fully collimated, the flow of ejecta from a rotating discrete source will fill a conical surface (if the emission is continuous) or a part of it (if the emission is interrupted during the diurnal cycle). Unless Earth is in the volume of space that is circumscribed by this emission cone, the latter will project onto the plane of the sky as a fan pointing in the general direction of, but not exactly at, the Sun. If the emission proceeds continuously throughout the rotation, the fan's axis coincides with the comet's projected spin axis and the fan's cone angle measures the angular deviation of the ejection vector from the spin axis; that is, it correlates with the cometocentric co-latitude of the source. For comets such as Encke's, with persistent fans of a relatively small cone angle, these conditions imply that the source is near the sunlit rotation pole, which in turn points approximately at the Sun. One thus arrives at an important conclusion that *a comet of fan-like appearance has its spin axis oriented close to the orbital plane* (a high-obliquity configuration). The presence of a fan also implies that



SHARPLY-PEAKED EMISSION WITH THERMAL LAG

CONTINUOUS EMISSION (CIRCUMPOLAR SUN)

QUASI-CONTINUOUS EMISSION (SUNRISE TO SUNSET)

FIG. 7—Schematic representation of two concepts for the formation of a sunward fan of a rotating comet. The model with sharply-peaked emission and thermal lags (left) has the fan's apex at the point of maximum activity on the parallel of subsolar latitude, the cone axis coinciding with the direction of the expanding ejecta. For the continuous (centre) and quasi-continuous (right) collimated emission models, the fan's apex is at the point of intersection of the cone axis and the extension of the spinning emission vector, the axis coinciding with the rotation vector. Also shown are the equator, the location of the emission source and its parallel of latitude, the sense of rotation, and the Sun's direction. (Reproduced from Sekanina 1987.)

the nucleus must be in the state of virtually pure spin, as a "smear" caused by significant precession on time scales shorter than, or comparable to, the residence time of the ejecta in the fan would render the latter undetectable. Finally, to make the fan appear virtually structureless on linear scales characteristic of Earth-based images requires rather a high spin rate, unless there are several sources in the active zone or unless the source covers a very extensive area. Depending on the near-nucleus flow properties, gaseous emissions from discrete sources may also produce a fan-like coma, but its boundaries are generally less well defined because of a more chaotic distribution of molecular motions and randomization effects of photodissociation on the dynamics of daughter products.

Experience with the two concepts of fan formation, which are schematically compared in figure 7, has shown the collimation model to be vastly superior and almost certainly correct, allowing a straightforward determination of the spin-vector orientation. On a co-ordinate chart, the rotation-pole positions consistent with a given axial direction of the fan lie on a great circle passing through the axis. Position-angle data obtained at different times thus provide a set of great circles all of which must intersect at the same two points, whose co-ordinates are those of the rotation poles. In practice, because of observational errors involved, each great circle becomes a narrow slice delimited by two great circles that

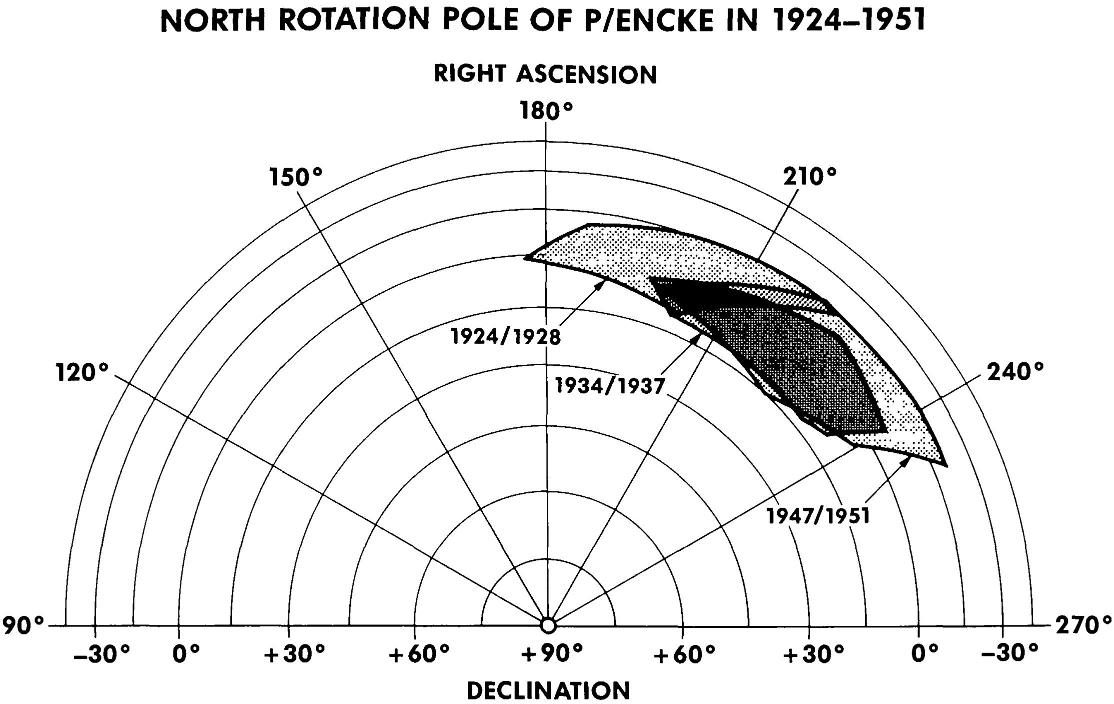


FIG. 8—Constraints on the position of the rotation pole of Encke's comet from observed orientations of the fan. Based on the combined common solutions for the apparitions 1924–1928, 1934–1937, and 1947–1951. (Reproduced from Sekanina 1988b.)

correspond to the error bounds. A solution common to all of them is identified as the area of overlapping slices. An example for Encke's comet is depicted in figure 8, on which the solutions for the position of the rotation pole at the apparitions of 1924–1951 are shown by the dark area, common to the solutions for the apparitions of 1924–1928, 1934–1937, and 1947–1951. Information on the comet's fan orientation at 13 apparitions between 1924 and 1984 is consistent with an invariable position of the rotation pole near R.A. (1950) = 205°, Decl. (1950) = +2°, so that the comet's precession during the 60 years was apparently very slow, if any (Sekanina 1988b). An extension of the study of the orientation pattern of the pre-perihelion fan back in time to 1868 (Sekanina 1988a) did result in the detection of measurable nucleus precession of Encke's comet, its time-variable rate averaging about 1° per revolution between 1868 and 1984, but more than 3° per revolution in the second half of the 19th century. The results of this investigation are compared with the precession model of Whipple and Sekanina (1979) in figure 9. The obliquity of the comet's orbit plane to its equatorial plane varied between 69° and 76° during the whole period of time. Reported instances of the comet displaying no sunward fan before perihelion (Sections 5.4 and 5.5) were shown to be of diagnostic value because they refer consistently to

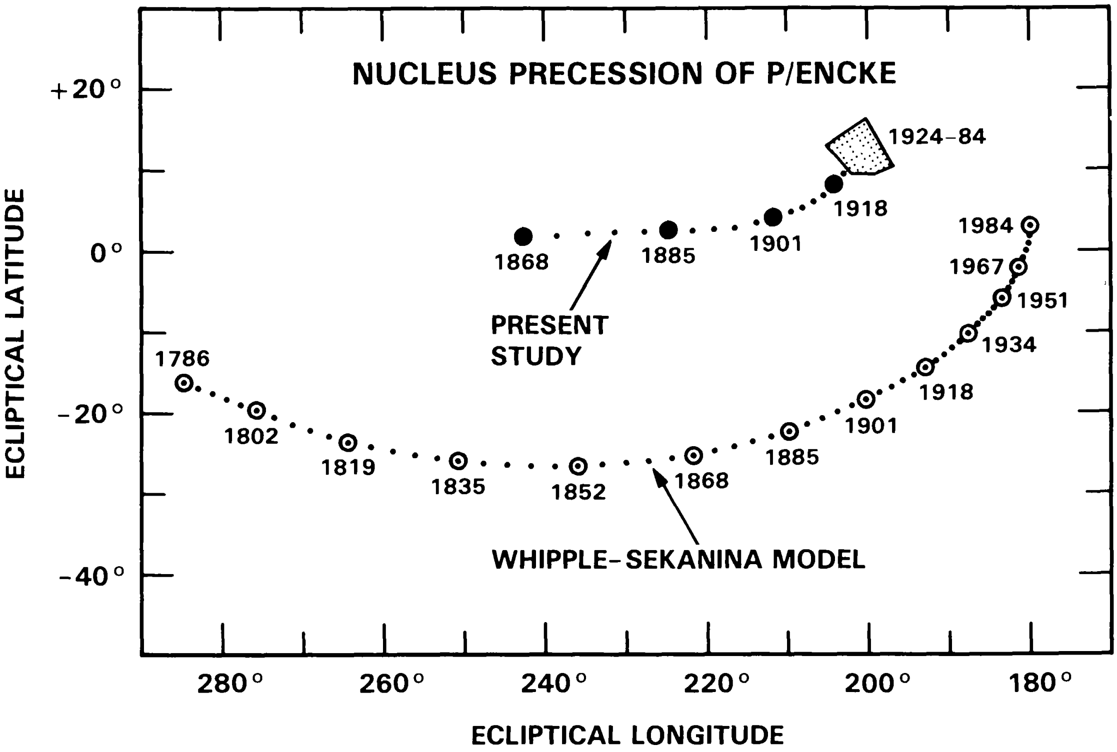


FIG. 9.—The precession of Encke's comet derived from the collimated fan model (referred to as PRESENT STUDY) and from Whipple-Sekanina's (1979) model. (Reproduced from Sekanina 1988a.)

configurations in which the aspect angle (the angle that the comet–Earth vector makes with the comet's spin vector) was near zero; that is, when Earth was in the volume of space circumscribed by the comet's emission cone (Sekanina 1988a). These configurations are easy to identify as they occur during a pre-perihelion observing window at the apparitions at which the comet's perihelion passage takes place in mid-April.

The calculated position of the comet's spin vector implies peculiar seasonal variations for the two polar hemispheres. With the present rotation-pole coordinates, one finds that the Sun transits the comet's equatorial plane about 8 days before perihelion, when the comet's heliocentric distance is 0.40 AU, and again 65 days after perihelion, at a distance of 1.35 AU. Thus, the Sun stays on one side of the equator for 1127 days, or 94 per cent of the 1200 days that Encke's comet needs to complete one heliocentric orbit! However, it is in the remaining 6 per cent of the orbital period that the comet passes through perihelion. Such an extremely uneven exposure is bound to have a profound effect on the thermophysical properties and evolution of the two hemispheres, especially their polar regions. Furthermore, the same hemisphere that is turned to the Sun at the times the comet displays its pre-perihelion fan is also predominantly sunlit throughout the orbit's aphelion arc, providing favourable conditions for activity at large heliocentric distances. The real possibility of a contamination of the comet's near-aphelion images by lingering, low-velocity solid ejecta is a major obstacle standing in the way of obtaining good estimates for the nucleus dimensions. Other drawbacks of the optical techniques for the nucleus-size determination include the unknown albedo of the object and its uncertain phase law. Under these circumstances, the agreement among the various published values for the average nucleus radius of Encke's comet (e.g., Roemer 1966, Sekanina 1986, Jewitt and Meech 1987, Ferrin and Gil 1988, Luu and Jewitt 1990), clustering about 2–4 km for an assumed geometric albedo near 0.05, is all one can hope for. These estimates are generally consistent with those derived by other methods, which have their own weaknesses and which are based on infrared observations (Campins 1988, Gehrz *et al.* 1989), radar techniques (Kamoun *et al.* 1982), or dynamical models (Whipple 1951, Whipple and Sekanina 1979).

The determination of the locations of discrete sources of activity on the surface of the nucleus of a comet is a difficult task that requires a detailed set of observations in order to be fully tractable. The underlying assumption is that the sources of localized outgassing coincide with the regions of observable dust emission. The longitudes of these areas can be derived only from the nucleus-subtracted rotational light curves of the dust ejecta, not yet available for Encke's comet. On the assumptions that only one source is active at a given time and that the ejecta flow is perfectly collimated, the angular distance of the ejection vector (that is, the normal to the source's surface) from the spin axis – a quantity related to the cometocentric latitude of the source – is defined as one half the cone angle of the emission fan observed at the aspect angle of 90°. Corrections for other aspect angles can straightforwardly be calculated, as long as Earth is located outside the volume of space circumscribed by the emission cone. (If Earth is inside that volume, the emission cone will appear as an oval or a round coma, with the nucleus near or at its centre.) The cone angle should be measured in the immediate proximity of the nucleus, since, because of the gradual randomization of dust-particle motions, the degree of the flow's collimation generally decreases with increasing distance from the nucleus. This effect is readily seen by comparing the smeared boundaries of the fan on the moderate-resolution images in figure 3 with its sharp boundaries on the high-resolution image in figure 4 (note the vastly different scales of the two figures). From the cone-angle estimates on photographs taken between 1924 and 1980, the polar distance of the ejection vector of the source responsible for the pre-perihelion fan was found to amount to about 35°, while from the IUE observation of the post-perihelion fan in 1984 (Section 5.5), it was tentatively estimated that the ejection vector of this second source makes an angle of some 15° with the direction to the opposite rotation pole (Sekanina 1988b).

The identification of *two* sources, one located near one rotation pole and ac-

TABLE II
DIURNAL REGIMES OF INSOLATION FOR THE TWO DISCRETE EMISSION SOURCES ON THE NUCLEUS OF ENCKE'S COMET AT THE 1990 APPARITION (UPDATED FROM SEKANINA 1988B)

			"Pre-perihelion" source		"Post-perihelion" source	
Polar-day regime	Day-and-night regime	Polar night regime	Time from perihelion[a] (days)	Distance from Sun (AU)	Time from perihelion[a] (days)	Distance from Sun (AU)
begins	ends	—	+353	3.61	−5	0.36
ends	begins	—	−19	0.59	+38	0.94
—	ends	begins	−2	0.33	+124	2.07
—	begins	ends	+22	0.63	−12	0.45

[a] Negative times are before perihelion; positive, after perihelion.

TABLE III
ORBITAL DISTRIBUTION OF THE DIURNAL REGIMES OF INSOLATION FOR THE TWO SOURCES ON THE NUCLEUS OF ENCKE'S COMET AT THE 1990 APPARITION

	"Pre-perihelion source"			"Post-perihelion" source		
Insolation regime	Duration (days)	Relative duration[a]	Insolation (kcal/cm^2)	Duration (days)	Relative duration[a]	Insolation (kcal/cm^2)
Polar day	828	69	254	43	3	364
Day and night	348	29	108	93	8	22
Polar night	24	2	0	1064	89	0

[a] In percentage of the orbital period (rounded off to 100 per cent).

tive primarily before perihelion, and the other situated near the opposite pole and activated for only a limited period of time around and after perihelion, provides an entirely new scenario for interpreting the observed water-production curve. The diurnal insolation patterns at the two locations are described in terms of the polar-day, polar-night, and day-and-night regimes in Tables II and III, which illustrate the enormous disparities between the distributions of incident solar energy along the comet's orbit. Although the Sun is circumpolar (the polar-day regime) for almost 70 per cent of the time at the "pre-perihelion" source, this region receives about as much solar energy per unit surface area during the whole orbital period as the "post-perihelion" source gets in the six weeks under the polar-day conditions. A simple model for water sublimation from a flat surface, which accounts for the expected diurnal and seasonal variations in the production rate from point-like emission centres, yielded the effective outgassing areas of 0.4 and 0.6 km^2, respectively, for the "pre-perihelion" and "post-perihelion" sources (Sekanina 1988b). The rotation-averaged water-production curve derived from this model is represented by the solid curve in figure 6. Except for vertical shifts that determine the outgassing areas (assumed not to vary with time), the curve is *not* a fit to the data points. The fluctuations during the several weeks preceding the comet's perihelion passage (including the major drop detected by A'Hearn, Millis and Thompson 1983), which are not matched by the rotation-averaged curve, may be explained as by-products of the "pre-perihelion" source's rapidly approaching transition from the polar-day regime (calculated to terminate about 19 days before perihelion; Table II) to the polar-night regime (which begins about 2 days before perihelion). Almost simultaneously, the "post-perihelion" source transits from the polar-night regime (terminating some 12 days before perihelion) to the polar-day regime (beginning 5 days before perihelion). As the polar-day regime nears its final days at the location of the "pre-perihelion" source, the diurnal variations in the insolation rate become very large because of the considerable variations in the Sun's elevations above the local horizon between noon and midnight. These effects are likely to result in major water-production fluctuations that might become erratic during the transitional period of rapidly changing thermal conditions.

Although one cannot rule out the existence of limited activity from other areas of the nucleus, it appears highly probable that the two discrete sources dominate the comet's outgassing pattern. It is hoped that future observations will provide further tests for the proposed two-source model.

5.9. New solutions to the orbit determination problem. Whipple's model and other major advances in the physical theory of comets stimulated the development of innovative techniques for investigating cometary motions. A radically new approach to the orbit determination problem in the presence of recoil-force perturbations was initiated by B.G. Marsden in the late 1960s. He introduced the non-gravitational acceleration **N** directly into the equations of motion of a comet, which he writes symbolically in the form (Marsden 1987)

$$\ddot{\mathbf{r}} = -k^2 \frac{\mathbf{r}}{\|\mathbf{r}\|^3} + \nabla G + \mathbf{N}, \tag{8}$$

where k^2 is the Gaussian gravitation constant, **r** is the Sun-comet vector, ∇ is the vector operator for partial differentiation, G is the disturbing function describing the sum of the gravitational perturbations by the planets,

$$G = k^2 \sum_{i=1}^{n_p} m_i \left(\frac{1}{\|\mathbf{r}_i - \mathbf{r}\|} - \frac{\mathbf{r} \cdot \mathbf{r}_i}{\|\mathbf{r}_i\|^3} \right), \tag{9}$$

$\mathbf{r}_i$ is the position vector of the i-th planet relative to the Sun, m_i is the i-th planet's mass in units of the Sun's mass, and n_p is the number of planets whose gravitational attractions are incorporated in the orbital solution. If $\mathbf{h} = \mathbf{r} \times \dot{\mathbf{r}}$ is the comet's orbital angular-momentum vector, the expression for the non-gravitational acceleration is generally

$$\mathbf{N} = q_1 \frac{\mathbf{r}}{\|\mathbf{r}\|} + q_2 \frac{\mathbf{h} \times \mathbf{r}}{\|\mathbf{h}\| \, \|\mathbf{r}\|} + q_3 \frac{\mathbf{h}}{\|\mathbf{h}\|}, \tag{10}$$

where q_1, q_2, and q_3 are the three orthogonal components of the acceleration, respectively, in the direction of the prolonged radius vector, in the direction perpendicular to the sunward direction in the orbit plane in the sense of the comet's orbital motion, and in the direction of the northern orbital pole. After some experimentation with the functional form for q_i (Marsden 1969, 1970, Marsden, Sekanina, and Yeomans 1973), the following law was finally employed for large scale calculations:

$$q_i(r) = A_i \alpha (r/r_0)^{-m} [1 + (r/r_0)^n]^{-l}, \; i = 1, 2, 3, \tag{11}$$

where r is a heliocentric distance, r_0, m, n, and l are positive constants, and α is a normalization coefficient such that $q_i = A_i$ at $r = 1$ AU. Since the law (11) is symmetrical with respect to perihelion, the contribution from the radial component to the anomaly in the mean motion essentially cancels and the observed effect is due to the transverse component. The normal component has a periodic character and the calculations have shown that its effect is almost always negligible. In Marsden's approach, allowance for long-term variations in the non-gravitational perturbations is done in one of two ways: (i) by introducing constants B_i, usually in exponential terms of the type $A_i = A_{0i} \exp[-B_i(t - t_0)]$, where A_{0i} are the acceleration components at time t_0, or (ii) by linking a sufficiently small number of apparitions, so that $A_i =$ const. ($B_i = 0$) is an acceptable approximation. Using the latter approach and limiting the number of apparitions linked in a single run to not more than five, Marsden and Sekanina (1974) provided 16 non-gravitational solutions for Encke's comet, spanning the 1786–1971 apparitions. The history of the comet's mean-motion anomaly during the two centuries of observations, 1786–1987, is displayed in figure 10, based on updated information (Marsden 1989). The time co-ordinate plotted is the middle of the time span covered by each computer run. Compared with non-gravitational anomalies of other short-period comets, the effects on the motion of Encke's comet are known to have varied fairly smoothly with time. However, Marsden and Sekanina (1974) commented on considerable difficulties they experienced with the orbital solutions that included the apparitions of 1868 and

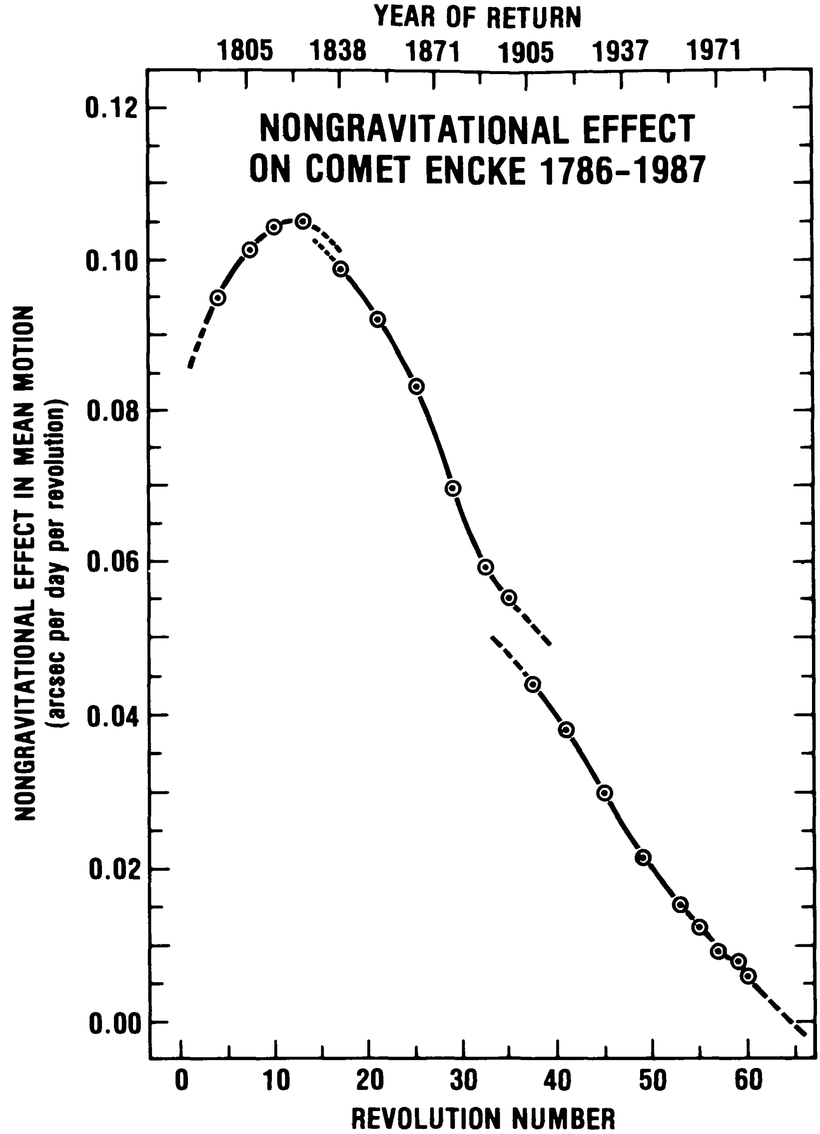


FIG. 10.—Non-gravitational anomaly in the mean motion of Encke's comet between 1786 and 1987. The dashed parts of the curve are extrapolations, some of them emphasizing the magnitudes of the discontinuities. (Adapted from Marsden and Sekanina 1974 and updated with the data from Marsden 1989.)

1898. Interestingly, these are essentially the same times that caused problems to von Asten and Backlund and that led the latter to the conclusion that the acceleration was decreasing stepwise. These discontinuities are also detected as sudden changes in the slope on a plot of residuals that the observed times of perihelion passage yield with respect to a prescribed smooth law. For example, one of Sitarski's (1987) polynomial representations of the non-gravitational variations in the semi-major axis produces the residuals shown in figure 11. Following

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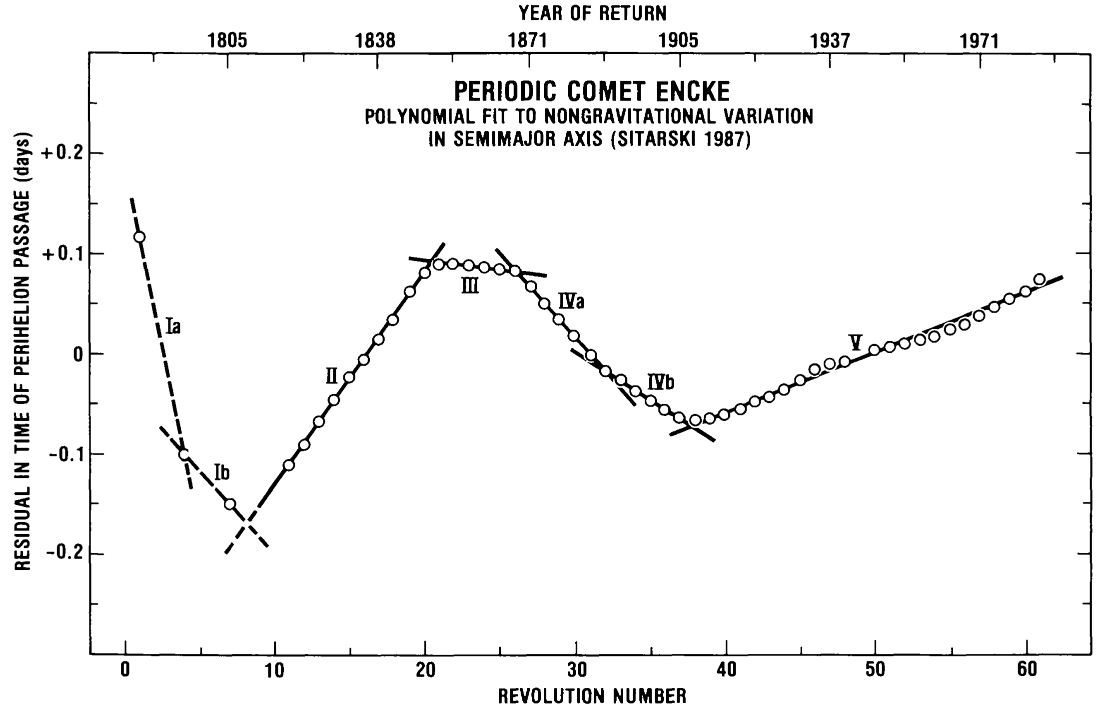

FIG. 11—Temporal variations in the residuals between the observed times of perihelion passage of Encke's comet and their calculated values from Sitarski's (1987) cubic fit to the non-gravitational perturbations of the comet's semi-major axis. The curve is divided into several sections, identified by the roman numerals, within which the residuals can be fitted by straight lines. Sharp changes in the slope between neighbouring sections could be associated with discontinuities in the perturbations. (Reproduced from Sekanina (1991) with permission of Kluwer Academic Publishers.)

the poorly defined early portion of the curve (Sections Ia–Ib), the slopes are virtually constant during the time periods identified as sections II, III, IVa–IVb, and V. Major events appear to have occurred shortly after 1800, about 1850, in the late 1860s, and at the beginning of the 20th century. A minor event before 1890 is doubtful. The slopes of the curve of residuals are unimportant, because they depend primarily upon the choice of the fitting law. Unfortunately, some of the resulting slope turnovers can also be artifacts of the law employed, so that caution ought to be exercised in the interpretation. However, at least two correlations persist between the curves in figures 10 and 11, pointing again to the discontinuities in the late 1860s and just before 1900.

Even though the approach to the orbit determination problem described by equations (8) through (11) represents a great improvement over the earlier techniques, one should be aware of the fact that for at least two reasons it, too, is only an approximation. One reason is, of course, the postulated symmetry of the non-gravitational law with respect to perihelion, while the other is the assumed invariability of the parameters A_i (or A_{0i}). On the other hand, these approximations make the orbit determination problem readily tractable without the knowledge of the comet's rotational parameters, the source function, and the momentum-distribution law. In addition, from a pragmatic point of view, the application of this approach is justified by demonstrated superior predictive properties and by the fact that the magnitude of the total non-gravitational effect in the mean motion is not very sensitive to the heliocentric variations assumed. Nevertheless, the role of perihelion asymmetry in the momentum transfer to the nucleus was addressed on several occasions. The early work employing modern computer techniques showed that orbital solutions based on asymmetric laws failed to improve the fit to the positional observations for reasons that are not fully understood. Supporting evidence is provided by Marsden (1970) for Encke's comet and by Yeomans (1984) and Landgraf (1986) for Halley's comet. More recently, however, Yeomans and Chodas (1989) succeeded in improving positional residuals for several short-period comets, employing Sekanina's (1988a) suggestion that the desirable asymmetry could be achieved by applying the "standard" law (11), in which heliocentric distance is taken not at the observation time t, but at a time $t - \tau$. The non-gravitational acceleration then peaks either before perihelion if $\tau < 0$, or after perihelion if $\tau > 0$. This model has not yet been applied to Encke's comet.

6. Current trends and future research. The large amount of recently acquired information on the activity of Encke's comet and the refined knowledge of the temporal variations in the non-gravitational perturbations of its orbital motion make it possible to offer a fairly detailed scenario for the probable events that take place on the comet's nucleus and that are responsible for the observed phenomena.

Since sublimation of water ice and other volatile substances and ejection of the dust entrained in the gas flow lead necessarily to gradual surface erosion of the emission regions, one can expect that especially the sources that have been active for a long time should appear as major depressions with respect to the surrounding inert surface. On certain assumptions it is possible to estimate the erosion rate per revolution about the Sun as a function of the comet's orbital dimensions, the nucleus spin vector, and the source's location on the surface. This erosion rate is a measure of the potential life span of the source and, indirectly, it yields information on the history of the comet's activity. The model for Encke's comet described in Section 5.8 offers an opportunity to estimate the depths of the two sources (Sekanina 1988a). The integration of the water-production law (figure 6) over the entire orbit yields a total mass-loss rate of nearly 5×10^{12} g of water per revolution in recent times, of which less than 30 per cent is contributed by the "pre-perihelion" source and the rest is accounted for by the "post-perihelion" source. Considering the sizes of the outgassing areas involved (Section 5.8) – implying effective diameters on the order of 0.8 km –

the above figures are equivalent, respectively, to the normalized loss rates of 350 and 580 g/cm^2 of water per revolution. With a conservatively estimated value of 0.5 g/cm^3 for the average bulk density of the nucleus, the layer of water ice sublimated away in one revolution, 7–12 metres, is enormous. If continuing at this rate, outgassing from either of the two sources would produce a local depression with a diameter-to-depth ratio of 1:1 in not more than 100 revolutions, and its depth would approach the dimensions of the nucleus in several hundred revolutions about the Sun. For a lower density (such as advocated by Rickman 1986 or Greenberg 1986), the excavation time scales would be shorter still. It therefore appears that because the high erosion rates cannot be sustained for very long, the life spans of localized active centres on Encke's comet must be very short compared with the life-time of the comet's nucleus. It also appears that any isolated emission region that does not become extinct within a limited period of time after activation is turned into what can appropriately be described as a *vent*. These conclusions are strengthened by the results of Colwell *et al.*'s (1990) recent modelling efforts, which indicate that the maximum outgassing rate from a crater-like depression is reached at its floor.

If the life spans of active regions are fairly limited, then expiring vents should be replaced with new vents at a rate of perhaps one per several hundred years or so, or else the nucleus becomes entirely void of activity. The birth of a new vent (as well as the extinction of an expiring vent) is bound to bring about a major redistribution of the momentum transferred to the nucleus. Hence, such an event should show as one or more discontinuities on the curve of non-gravitational perturbations of the comet's mean motion, especially if the new vent's activation involves an irregular, erratic spewing of gas, whether due to a complex topography or a peculiar distribution of ices at the location.

The collimation of the ejecta flow from a vent, so amply illustrated on the remarkable close-up images of the nucleus of Halley's comet taken with the *Giotto* camera (Keller *et al.* 1987), is expected to be correlated with the vent's diameter-to-depth ratio. Hence, for a given diameter, collimated jets should be diagnostic of deep, and therefore old, vents, while shallow, recently activated vents may not display any jets that would be detectable by terrestrial observers. What kind of physical changes – besides getting deeper – aging vents are subjected to is, of course, unknown, but their evolution unquestionably depends upon their morphology. If, instead of being a simple crater-like structure, a vent is made up of a complicated system of intertwined channels or interstitial crevices of various dimensions penetrating into the nucleus interior, the effective diameter-to-depth ratio would be reduced dramatically and the flow collimation increased even further. As a result, however, the floor's exposure to sunlight would be significantly restricted, causing the highly structured walls to account for virtually all the region's emission and thus increasing its effective diameter-to-depth ratio.

Another question for which there is as yet no answer is whether the conditions on the nucleus would ever allow a vent to achieve a depth comparable to the dimensions of the nucleus. Depending upon the mechanical and morphological properties of the region in question and upon an interplay of the processes that cause the vent to evolve, plausible scenarios – such as a partial wall collapse in the course of continuing outgassing – may temporarily interrupt or even terminate the vent's erosion process. Perhaps it is the competition between the erosion and the vent-destruction processes under the conditions of microgravity and a hostile radiation environment that is responsible for the puzzling, erratic temporal variations in the activity of isolated vents. With all these possibilities kept in mind, it becomes increasingly obvious that the evolution of an active region in one part of a comet's nucleus is largely independent of the evolution of another active region situated elsewhere on the surface. The only global-scale process that could provide a kind of "communication" among individual centres of activity is random deposition – with the possibility of a gradual regolith-type build-up – of fine dust grains entrained in the surface breeze of the circumnuclear pressure-equalization gas flow (e.g., Keller *et al.* 1987; Kitamura 1987). Unless this process plays a major role in the surface evolution of the nucleus, attempts to describe the aging of comets in terms of characteristics of the nucleus as a whole are too simplistic for objects with discrete active centres, such as Encke's comet. The traditional perception of cometary deactivaton as a slow, monotonic process that concludes with the object's irreversible extinction needs to be replaced with a more dynamic concept of intermittent periods of dormancy and reactivation of isolated vents.

The issue of independent evolutionary paths of individual sources on a given comet nucleus entails an interesting possibility of having *no* vent active during certain, perhaps prolonged, periods of time – the case of a dormant comet. Encke's comet once again offers itself as an attractive candidate for such developments. Indeed, Whipple and Hamid's (1972) search for pre-1786 records on the comet among nearly 600 transient objects in Ho's (1962) catalogue that covers the period of time until 1600 A.D. led to no positive identification, raising questions of (i) possible inactivity of Encke's comet over extensive periods of time after the Taurid meteor complex had been produced several thousand years ago (Whipple and Hamid 1952) and (ii) its possible reactivation at some time during the 17th or the 18th century. One also wonders what appearance and outgassing characteristics is the comet likely to possess in the 21st century.

While it is impossible to answer these questions unequivocally, the curve of the non-gravitational anomaly in figure 10 provides some interesting insights. The two-source model (Section 5.8) applied to recent apparitions (in the 1980s) indicates that (i) more than 60 per cent of the calculated perturbation effect in the mean motion generated by either of the two vents is due to the *radial* component, arising from the perihelion asymmetry of the water-production curve;

(ii) the integrated contribution from the radial and transverse components are of the same sign, reinforcing each other's effect; (iii) the combined contributions from the "pre-perihelion" and "post-perihelion" sources accelerate the nucleus over some arcs of the orbit but decelerate it over other arcs; and (iv) the observed non-gravitational anomaly has the same sign as the calculated contribution from the "pre-perihelion" source but opposite to that from the "post-perihelion" source, which implies that the momentum-transfer efficiency of the latter source is substantially lower than that of the former source (Sekanina 1988a). Combined with other, already mentioned, evidence, these results suggest that the "pre-perihelion" vent is of advanced age and substantial depth. Indeed, its existence is documented by observations of the associated fan as early as 1805 (figure 1) and its depth can be estimated at probably not less than ~0.5 km and possibly more than 1 km. The early increase in the non-gravitational acceleration, clearly apparent in figure 10, implies a strongly increasing perihelion asymmetry of the comet's activity, compatible with a rapidly expanding area of the vent. Extrapolating back in time prior to 1786, one can estimate that this vent may have become activated as late as ~1750. Unless another vent had been active before then, the entire nucleus surface of Encke's comet may indeed have been dormant in earlier times, a conclusion that is consistent with Whipple and Hamid's (1972) failure to find any record on the comet before 1600 A.D.

The gradual decrease in the non-gravitational acceleration ever since the 1820s may be explained most probably by a combined effect of the comet's forced precession, the decreasing outgassing area of the "pre-perihelion" vent, and – later – the increasing outgassing area of the "post-perihelion" vent. The gradually increasing activity of this latter source is consistent with the changing shape of the comet's light curve near perihelion in recent times (figure 5) and the source's current high rate of outgassing is obvious from the water production curve in figure 6. It is reasonable to speculate that this vent did not become activated until the mid- or late 19th century – coinciding with the discontinuities on the curve of the non-gravitational perturbations in figure 10 – and that until recently it had been so shallow as to exhibit no fan-shaped coma, as apparent from the negative observations before 1961 (Section 5.8).

Further monitoring of Encke's comet throughout its orbit is necessary to verify and refine its current emission model and to address the crucial issues involved, such as why and how the discrete regions get activated, how they evolve, and why and how they become extinct. For a brief outlook ahead, the reader can consult Table IV, which lists some basic information on the comet's six upcoming returns: the type of return from the standpoint of Earth-based observability, the comet's maximum elongations from the Sun, and the expected orientation and appearance of the emission fan. If the evolution of the two major vents on the nucleus surface continues uninterrupted by new unexpected developments,

TABLE IV

Perihelion Returns of Encke's Comet between 1994 and 2010

	Year of perihelion passage					
	1994	1997	2000	2003	2007	2010
Type of return[a]	mixed	post	mixed	pre	mixed	post
Maximum elongation from Sun[b]						
before perihelion	83°	19°	43°	138°	37°	25°
after perihelion	53°	128°	36°	29°	107°	56°
Fan orientation and appearance[c]						
40 days before perihelion	W	(*NNE*)	ENE	W	(*NW*)	(ENE)
20 days before perihelion	W	(*NE*)	(E)	(W)	(*N*)	(E)
20 days after perihelion	E	(W)	(S)	(E)	(*NW*)	WSW
40 days after perihelion	E	W	SE	(E)	NE	SSE

[a] Observability: pre = the comet observable pre-perihelion from the northern hemisphere; post = the comet observable post-perihelion from the southern hemisphere; mixed = the comet observable both before and after perihelion.

[b] Within 60 days of perihelion passage.

[c] Roman letters indicate that Earth will be outside the volume of space circumscribed by the emission cone (favourable circumstances); italic letters indicate that Earth will be inside that volume of space (unfavourable circumstances); parenthesized entries indicate the comet's elongation from the Sun will be less than 30°.

the activity pattern of Encke's comet is likely to change dramatically in the 21st century. Indications are that the centre of activity will be shifting ever more to the polar hemisphere that is sunlit after perihelion, which is when the comet should ultimately become much brighter. This trend may be even more pronounced if the "post-perihelion" source should further grow and attain a substantially greater outgassing area than the estimated one per cent or so of the nucleus surface that the two sources appear to occupy nowadays (Sekanina 1988b; see also Jewitt and Meech 1987, Rickman *et al.* 1987, Delsemme and Rud 1973, and Fanale and Salvail 1984).

Our knowledge of the comet, although by no means entirely satisfactory, has come a long way since the recognition of its orbital periodicity by J.F. Encke. If this remarkable scientist could be brought to life today, he might be upset about the proven failure of his resisting-medium hypothesis, but I believe that he would be both delighted and amazed that *his* comet continues to enjoy considerable interest of the scientific community and that almost two centuries after his discovery it still plays a major role in the quest for a better understanding of cometary phenomena.

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Z. Sekanina,
Jet Propulsion Laboratory,
California Institute of Technology,
Pasadena,
California 91109,
U.S.A.

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