Later commentators have said that Francis preached to the birds as a rebuke to men who would not listen. The records do not read so: he urged the little birds to praise God, and in spiritual ecstasy they flapped their wings and chirped rejoicing. Legends of saints, especially the Irish saints, had long told of their dealings with animals but always, I believe, to show their human dominance over creatures. With Francis it is different. The land around Gubbio in the Apennines was being ravaged by a fierce wolf. Saint Francis, says the legend, talked to the wolf and persuaded him of the error of his ways. The wolf repented, died in the odor of sanctity, and was buried in consecrated ground.

What Sir Steven Ruciman calls "the Franciscan doctrine of the animal soul" was quickly stamped out. Quite possibly it was in part inspired, consciously or unconsciously, by the belief in reincarnation held by the Cathar heretics who at that time teemed in Italy and southern France, and who presumably had got it originally from India. It is significant that at just the same moment, about 1200, traces of metempsychosis are found also in western Judaism, in the Provençal *Cabbala*. But Francis held neither to transmigration of souls nor to pantheism. His view of nature and of man rested on a unique sort of pan-psychism of all things animate and inanimate, designed for the glorification of their transcendent Creator, who, in the ultimate gesture of cosmic humility, assumed flesh, lay helpless in a manger, and hung dying on a scaffold.

I am not suggesting that many contemporary Americans who are concerned about our ecologic crisis will be either able or willing to counsel with wolves or exhort birds. However, the present increasing disruption of the global environment is the product of a dynamic technology and science which were originating in the Western medieval world against which Saint Francis was rebelling in so original a way. Their growth cannot be understood historically apart from distinctive attitudes toward nature which are deeply grounded in Christian dogma. The fact that most people do not think of these attitudes as Christian is irrelevant. No new set of basic values has been accepted in our society to displace those of Christianity. Hence we shall continue to have a worsening ecologic crisis until we reject the Christian axiom that nature has no reason for existence save to serve man.

The greatest spiritual revolutionary in Western history, Saint Francis, proposed what he thought was an alternative Christian view of nature and man's relation to it: he tried to substitute the idea of the equality of all creatures, including man, for the idea of man's limitless rule of creation. He failed. Both our present science and our present technology are so tinctured with orthodox Christian arrogance toward nature that no solution for our ecologic crisis can be expected from them alone. Since the roots of our trouble are so largely religious, the remedy must also be essentially religious, whether we call it that or not. We must rethink and refeel our nature and destiny. The profoundly religious, but heretical, sense of the primitive Franciscans for the spiritual autonomy of all parts of nature may point a direction. I propose Francis as a patron saint for ecologists.

One Hundred Periodic Comets

Modern techniques of observation and computation are enabling us to clarify our ideas about these bodies.

Brian G. Marsden

Although Seneca remarked almost 2000 years ago that comets were celestial bodies that might reappear periodically, ideas on the subject were dominated until the 16th century by the pronouncements of Aristotle and Ptolemy that comets were meteorological phenomena to be regarded as the forerunners of disaster.

The turning point came when Tycho Brahe showed the comet of 1577 to be more distant than Moon. Tycho supposed it to travel about Sun in a circular orbit somewhat larger than that of Venus. Curiously enough, Kepler never applied his laws of planetary motion to comets and believed them to move through the solar system in straight lines. Some of Kepler's contemporaries, however, such as Horatio Grassi and William Löwer, held that cometary orbits were indeed ellipses.

It was of course Newton who settled the question by demonstrating that the comet of 1680 moved, in accordance with the law of gravitation, in an orbit that was an ellipse of such great eccentricity that it could be approximated by a parabola. Shortly afterwards, in the course of his celebrated calculations on a number of comets, Halley noticed a resemblance among the orbits of the comets of 1531, 1607, and 1682; he deduced these to be one and the same body and predicted that it would return about the year 1758.

Other predictions, based on the similarity of various pairs of cometary orbits, were made from time to time by several astronomers during the 18th and 19th centuries. The futility of this practice was finally pointed out in the 1860's by Hoek (*1*). He suggested that there were many instances in which comets traveled essentially in the same orbit; presumably they were fragments of some comet that had disintegrated. The existence of these "comet groups" renders it impossible to decide whether two comets with similar orbits are identical or not, unless the revolution period of one of them can be derived unequivocally from the observations.

The first comet for which a meaningful elliptical orbit was obtained directly from observations was one discovered by Messier in 1770. Considerable diffi-

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culty had been encountered in attempting to fit a parabolic orbit, and Lexell (after whom the comet is named) determined that the orbit was in reality an ellipse with a period of only 5.6 years. The comet returned in 1776 but was badly situated and not observed. By some quirk of fate, Lexell's comet passed very close to Jupiter in 1779 and was deflected into a much larger orbit (*2*), so that it could not in future be seen from Earth; and the comet would also have been unobservable before an earlier approach in 1767.

The second successful prediction of a comet was realized in 1822. Encke had shown that one discovered by Pons in November 1818 had a period of only 3.3 years, and that it was identical with three earlier comets. Except for comet Wilson-Harrington (1949 III), which has a very uncertain orbit of period 2.3 years, Encke's has the shortest period established for any comet and has been observed on every subsequent return except in 1944.

The third success followed in 1832 when Biela's comet returned; and the fourth success, Faye's comet, came in 1850. By 1875 nine comets had been successfully predicted, and during the following half-century the number rose to 19. As I write, 51 different comets have been reobserved according to prediction, and, of these, 38 have revolution periods of less than 9 years. In addition, five comets of rather longer period have been almost conclusively identified with other comets seen previously, and the periods of two of them exceed 150 years. Fifty-six comets have thus been observed at more than one perihelion passage.

Several comets observed at only one perihelion passage travel in elliptical orbits of short period. By short-period comet we mean one having a calculated period of less than 200 years; such comets are often loosely referred to as "periodic comets," although most comets are really periodic. Forty-four periodic comets have been observed only once, 29 of them having periods of less than 9 years; there are just 100 known periodic comets in all. It would be useless to try and predict returns of most of the one-appearance comets, for they were not observed well enough for their orbits to be reliably determined. All but a handful are hopelessly lost; if they are ever reobserved, it will be by accident.

How many periodic comets remain to be discovered? There is no evidence that most of them have now been found, for the fraction of comets discovered that are periodic has been nearly constant at one out of four or five for the last century. Of the 28 new comets found since the beginning of 1960, six are periodic; all have periods of less than 16 years—three, less than 9 years. Certainly, new periodic comets tend now to be among the fainter comets discovered, but this is not invariably true: *P*/Honda-Mrkos-Pajdušáková (we use the symbol *P*/ to denote a periodic comet) was of magnitude 9 at discovery in 1948; *P*/Ashbrook-Jackson was perhaps as bright as magnitude 10; and comets Tuttle-Giacobini and Perrine were of comparable brightness when accidentally rediscovered by Kresák in 1951 and Mrkos in 1955, respectively.

One might expect that the large Schmidt reflectors and other wide-field telescopes constructed during the last 30 years would be ideal for discovering faint comets. The number of very faint comets reported, however, is extremely small. In 1924 Max Wolf found a new comet at magnitude 16, but only five comets discovered since then have been fainter. The periodic comet most recently announced was one of magnitude 17, located on eight plates taken in 1960 with the 48-inch (122-cm) Schmidt at Palomar during a search for asteroids (*3*). This search, judged to be complete to magnitude 20, revealed some 2000 new asteroids, but only the one comet was recognized. Searching Schmidt plates for faint comets is an extremely time-consuming operation; furthermore, close to the plate limit, comets can look very much like asteroids, and most astronomers tend to ignore asteroids. Perhaps it is not surprising that no comet fainter than magnitude 19 has ever been reported. On the other hand, short-period comets have been recovered at magnitude 20 or 21; then the plates had been taken specifically for the comets, however (generally with long-focus reflectors), the motions of the comets during the exposures were allowed for, and the observers knew almost precisely where to look.

We conclude that periodic comets will continue to be discovered at essentially the same rate, although most of them will be faint and may have periods exceeding 9 years. If further intensive surveys are made for asteroids, the proportion of periodic comets may even increase, for these surveys are concentrated on the ecliptic, where such comets are most likely to be found.

"Lost" Comets

A number of comets observed at several perihelion passages then disappeared; the most famous is *P*/Biela, which split in two in 1846. The fragments returned in 1852, but neither has been observed since. When Earth passed near the orbit of the comet in 1872 and 1885, a splendid shower of meteors was observed, and it is generally assumed that this was the final wreckage of Biela's comet.

By 1925, 30 comets had been observed at more than one perihelion passage; eight of them, however—more than one in four—were regarded as lost, having failed to appear for several revolutions. By 1950, the number of lost comets had risen to ten—of a total of 44.

Since then there has been dramatic improvement, and five of the lost comets have been reobserved. Two of them, *P*/Tuttle-Giacobini-Kresák and *P*/Perrine-Mrkos, were picked up accidentally, as I have mentioned. The first of these was observed so briefly in 1858 and 1907 that it was not clear how many circuits it had made about Sun meanwhile (*4*). Perrine's comet had been observed in 1896 and 1909, but subsequent attempts to recover it were in vain. Predictions had been supplied for the 1955 return, but the comet was somewhat outside their range and some five magnitudes brighter than expected.

The other three comets have been recovered recently as a result of accurate predictions by Schubart and myself, for which high-speed computers were used (*5*). Holmes's comet was first seen in 1892 and reobserved in 1899 and 1906; in view of its enormous fluctuations in brightness during 1892–93—at times it was visible with the naked eye, even though more than 1.5 astronomical units (2.2×10^8 kilometers) from Earth—and its extreme faintness at the following two returns, many astronomers presumed that the comet had ceased to exist. Nevertheless, after passing unobserved through perihelion seven times, *P*/Holmes was recovered by Elizabeth Roemer in 1964. Another long-lost periodic comet also had been visible with the naked eye shortly after its discovery by de Vico in 1844; although the orbit was quite well determined and careful searches were made during ensuing returns, the comet was missed until Swift accidentally rediscovered it in 1894. Further attempts to recover *P*/de Vico-Swift also failed, and it was not until 1965 that it was reobserved, by Klemola, on the basis of a prediction. The most recent instance of a lost comet's being recovered is of greater importance: *P*/Tempel-Tuttle, discovered in 1865, was identified as the parent comet of the celebrated Leonid meteors. It had long been suspected that the comet, which has a period of 33 years, was identical with one recorded by the Chinese in 1366. Recent computations by Schubart showed not only that this was so, but also that it had been recorded one morning in 1699 by Kirch. Although the comet was badly placed for observation in 1965, Schubart was able to identify images of it on four photographic plates.

Of the 56 comets of more than one appearance, five may still be considered lost; predictions have been supplied for their current returns (*6*). *P*/Tempel-Swift, last seen in 1908, was not recovered in 1963, being probably just too faint; a more-thorough search will be justified in 1969–70. *P*/Neujmin 2, observed only in 1916 and 1927, was not found in 1965 but was unfavorably placed, and efforts should be made to recover it in 1970–71. *P*/Tempel 1 and *P*/Brorsen, neither of which has been seen since 1879, are due to return in 1967. There are particularly good reasons for expecting the former to be found, although it will not be so well placed as in 1972. Finally there is *P*/Biela, not recovered in 1965, being badly situated; perhaps it has dissolved into a stream of meteors, although several other spectacular streams are known—consider the magnificent display of Leonids in 1966, for example—which are still accompanied by their parent comets. The orbit of Biela's comet requires further investigation, for it is by no means clear whether the components of the comet in 1852 were correctly identified with those in 1846; this point must be resolved before we can come to a definite conclusion regarding its demise.

Fading Comets

Do comets deteriorate noticeably between one return and the next? We know that matter is expelled from the heads of comets to produce tails, and that more is strewn in the orbit in the form of meteoroids.

Vsekhsvyatsky has provided a catalog of the absolute magnitudes of all comets for which orbits have been determined (*7*). Such magnitudes are reduced to a standard distance of one astronomical unit from both Earth and Sun, generally on the assumption that the brightness varies as the inverse fourth power of heliocentric distance. Taken at face value, Vsekhsvyatsky's figures imply rapid fading for almost all the periodic comets. In the case of *P*/Encke the fading amounts to two or three magnitudes per century. Estimates of cometary brightness are strongly dependent on the size of telescope used, however (*8*). Was the observer trying to measure the total luminosity of the comet or merely that of the nucleus? If some of the observations are photographic, there is even more dispersion: a long exposure may show a magnificent comet with a fine tail, but with a short exposure for astrometric purposes the comet is barely noticeable among the stars. It is not unusual for an observer to describe a comet visually as of magnitude 9, when on a short-exposure photograph it may be recorded as of magnitude 15. In the 19th century the measurements of brightness were visual, but in recent decades an increasing number, especially of the periodic comets, have been from short-exposure photographs. Thus an apparent large decrease in brightness is precisely to be expected!

Kresák (*9*) has attempted a more realistic determination of the rate of deterioration of Encke's comet by discussing observations that are comparable whether they were made in the 18th century or in the 20th. He discussed the estimates of brightest magnitude reported at each return, and these are invariably visual. Several solutions for the absolute magnitude were made, but all indicated a centennial rate of decrease of not more than 1.0 or 1.1 magnitudes.

If comets do indeed fade at the rate found by Vsekhsvyatsky, they should have been rather bright objects only a few centuries ago. Yet no prediscovery observations of any of the 38 more-than-one-appearance comets, having periods of less than 9 years, have been identified prior to those of Biela's comet in 1772 (*10*). Our calculations show that, if the decrease in brightness is negligible, on account of the previous character of their orbits, 13 of the comets would in fact have been completely unobservable before they were first reported. Twenty more comets could perhaps have been seen on one, two, or even three previous occasions, but it is scarcely surprising that they were missed. We are left with five comets—Encke, Brorsen, Honda-Mrkos-Pajdušáková, Grigg-Skjellerup, and Pons-Winnecke—that should have been seen before they were. All had rather small perihelion distances, however, and would have been somewhat difficult objects. Nevertheless, it might be worthwhile to examine the records for early observations of Encke's comet (*11*).

With the occasional exception of Encke's comet, it is rare for a periodic comet to become visible with the naked eye. So far during this century only *P*/Pons-Winnecke and *P*/Schaumasse have been observed without optical aid, when they were close to Earth in 1927 and 1952, respectively. The ancient records mention comets that moved rapidly and lacked tails. It is probable that some of these were short-period comets in proximity to Earth (*12*), but it would be very difficult to identify them with known ones.

There is no doubt that several comets exhibit enormous fluctuations in brightness. We have already mentioned the anomalous appearances of *P*/Holmes in 1892 and *P*/Perrine-Mrkos in 1955.

Several comets were unusually bright at discovery. The most extreme example of a comet of varying brightness is *P*/Schwassmann-Wachmann 1, which has a period of 16 years and a nearly circular orbit (eccentricity, 0.13) entirely enclosed by those of Jupiter and Saturn (*13*). To be observable at this great distance (it generally appears at magnitude 18 or 19) this comet must be one of the largest known. From time to time it flares in brightness: not uncommonly it appears at magnitude 13, and has been reported as bright as magnitude 9. Typically, it appears as a nearly stellar nucleus, embedded in a small coma about 0.1-minute across. Within 24 hours the nucleus may appear to brighten so much that it overwhelms the coma. Then a small expanding disk of nebulosity can be distinguished within 2 or 3 days; this continues to expand until the surface brightness drops too low against the sky background to be recorded further, and the nucleus reappears (*14*).

Here we shall be mainly concerned with the 38 more-than-one-appearance comets having periods of less than 9 years. In Table 1 the bodies are listed according to their current revolution periods; the orbits of all have been traced by electronic computer for some three centuries, and the elements for both the present and an epoch about 1725 are given. Some of the early orbits must be regarded as provisional because the starting data were not always satisfactory. A slight error may be grossly magnified by a close approach to Jupiter; if several encounters have occurred, the calculated former orbit may be completely incorrect. Even if we could obtain the best-possible starting data, the problem would be complicated by nongravitational forces that may have been acting. Encke was the first to claim the existence of a secular decrease in the period of his comet, and more recently secular changes have been presumed for other comets (*15*). The reality of the effect has been questioned (*16*), however, and the subject requires careful reexamination.

Although the current values of the periods range from 3.3 to 8.6 years, all but 11 lie between 6.3 and 7.8 years. The complete absence of periods between 5.5 and 6.2 years, both in 1965 and in 1725, is very striking. A period in this range would be very close to half that of Jupiter, and the perturbations would tend to repeat themselves every alternate revolution. As is well known, there is a similar gap in the distribution of the periods of the asteroids. It is rare for an asteroid to traverse from one side of the commensurability to the other. The situation is different with the comets, however, and only five of the eight comets now in the inner group have remained there since before 1725. Comets Pons-Winnecke, de Vico-Swift, and Forbes also were temporarily in the inner group, and *P*/Wirtanen will enter it in 1984. Generally the passage through the commensurability takes place in two stages: a close approach to Jupiter sets the comet almost exactly in resonance, and the next approach 12 years later carries it well across. *P*/Pons-Winnecke, however, has taken the best part of a century to pass through the gap. Sometimes the second approach to Jupiter returns the comet to its original side of the gap, as happened with comets Wolf-Harrington, Harrington, and d'Arrest; also, of course, with *P*/Lexell. All but seven of the 23 comets now having periods as long as 6.8 years have spent, or are about to spend, some time in the inner group or in the gap.

Many "Kirkwood gaps" are evident in the case of the asteroids (*17*), but the only other obvious gap in the distribution of the cometary periods occurs at 7.9 years—two-thirds of the period of Jupiter (*18*). Comet Oterma entered this resonance after a close approach to Jupiter a few years before its discovery in 1943. After three revolutions about Sun, in an orbit of eccentricity 0.14, there was another close approach to Jupiter in 1963, and the present orbit—with a perihelion distance of 5.4 astronomical units and a period of 19 years—is similar to the original one (*19*). Comet Arend, on the other hand, has remained almost exactly in the commensurability since before 1725. The situation at resonances of higher order than the first is more confused. Comet Borrelly has been af-

Table 1. Periodic comets of the Jupiter family that have been observed at more than one perihelion passage. Orbital elements are given for circa 1965 and circa 1725. Abbreviations: *P*, revolution period; *e*, orbital eccentricity; *q*, perihelion distance; *Q*, aphelion distance; ω, argument of perihelion (arc from the ascending node to the perihelion); Ω, longitude of the ascending node; *i*, orbital inclination; *L*, longitude of perihelion; *B*, latitude of perihelion; AU, astronomical unit.

Comet	Circa 1965									Circa 1725								
	P (yr)	*e*	*q* (AU)	*Q* (AU)	ω (deg)	Ω (deg)	*i* (deg)	*L* (deg)	*B* (deg)	*P* (yr)	*e*	*q* (AU)	*Q* (AU)	ω (deg)	Ω (deg)	*i* (deg)	*L* (deg)	*B* (deg)
Encke	3.3	0.85	0.34	4.1	186	334	12	160	− 1	3.3	0.85	0.34	4.1	181	337	14	158	0
Grigg-Skjellerup	5.1	.66	1.00	4.9	359	213	21	212	0	4.9	.73	0.77	5.0	185	29	13	214	− 1
Honda-Mrkos-Pajdušáková	5.2	.82	0.56	5.5	184	233	13	57	− 1	7.0	.68	1.19	6.1	155	261	15	56	+ 6
Tempel 2	5.3	.55	1.36	4.7	191	119	12	310	− 2	5.2	.55	1.34	4.7	176	126	12	303	+ 1
Brorsen	5.5	.83	0.53	5.7	18	98	24	115	+ 7	5.2	.70	0.90	5.1	359	108	49	107	0
Neujmin 2	5.5	.58	1.31	4.9	214	308	5	162	− 3	6.7	.46	1.94	5.2	137	0	12	137	+ 8
Tuttle-Giacobini-Kresák	5.5	.64	1.12	5.1	38	166	14	203	+ 8	5.3	.61	1.19	4.9	14	185	22	198	+ 5
Tempel 1	5.5	.52	1.50	4.7	179	68	11	247	0	6.5	.42	2.00	4.9	56	177	5	233	+ 4
Pons-Winnecke	6.3	.64	1.23	5.6	172	93	22	265	+ 3	6.2	.71	0.97	5.8	2	270	3	272	0
de Vico-Swift	6.3	.52	1.62	5.2	325	24	4	350	− 2	7.2	.43	2.12	5.3	184	145	7	329	0
Kopff	6.3	.56	1.52	5.3	162	121	5	283	+ 2	9.3	.34	2.89	5.9	320	283	8	243	− 5
Tempel-Swift	6.4	.54	1.59	5.3	164	240	13	44	+ 4	5.5	.61	1.20	5.0	7	33	20	40	+ 2
Giacobini-Zinner	6.4	.73	0.93	6.0	173	196	31	10	+ 4	6.9	.66	1.22	6.0	166	204	34	12	+ 8
Forbes	6.4	.55	1.54	5.4	260	25	5	285	− 2	6.4	.48	1.79	5.1	187	94	20	280	− 2
Schwassmann-Wachmann 2	6.5	.38	2.16	4.8	358	126	4	124	0	10	.16	3.8	5.3	356	117	1	113	0
Wolf-Harrington	6.5	.54	1.61	5.4	187	254	18	81	− 2	14	.11	5.2	6.5	32	277	22	307	+12
Wirtanen	6.7	.54	1.62	5.5	344	86	13	70	− 4	7.0	.52	1.76	5.6	214	230	8	84	− 4
d'Arrest	6.7	.61	1.37	5.7	175	144	18	318	+ 2	6.9	.65	1.28	6.0	163	161	5	324	+ 2
Biela	6.7	.76	0.84	6.3	254	214	8	108	− 7	7.0	.72	1.02	6.3	212	262	17	113	− 9
Perrine-Mrkos	6.7	.64	1.27	5.8	166	240	18	47	+ 4	6.8	.67	1.19	6.0	144	270	8	54	+ 4
Reinmuth 2	6.7	.46	1.93	5.2	45	296	7	341	+ 5	7.4	.34	2.51	5.1	6	328	13	333	+ 1
Brooks 2	6.7	.50	1.76	5.4	197	177	6	14	− 2	31	.45	5.5	14	2	187	6	189	0
Harrington	6.8	.56	1.58	5.6	233	119	9	352	− 7	6.5	.55	1.58	5.4	176	158	15	334	+ 1
Arend-Rigaux	6.8	.60	1.44	5.8	329	122	18	92	− 9	6.8	.62	1.38	5.8	309	146	13	96	−10
Johnson	6.9	.38	2.25	5.0	206	118	14	324	− 6	6.5	.39	2.12	4.9	180	131	15	312	0
Finlay	6.9	.70	1.08	6.2	322	42	4	4	− 2	6.4	.68	1.12	5.8	196	170	22	6	− 6
Borrelly	7.0	.60	1.45	5.9	351	76	31	68	− 5	7.1	.56	1.63	5.8	352	84	33	77	− 4
Daniel	7.1	.55	1.66	5.7	11	69	20	79	+ 4	6.7	.57	1.54	5.6	354	82	21	76	− 2
Harrington-Abell	7.2	.52	1.78	5.7	338	146	17	125	− 6	7.1	.54	1.71	5.7	334	161	12	135	− 5
Holmes	7.3	.38	2.35	5.2	22	330	20	350	+ 7	8.6	.22	3.3	5.1	0	342	21	342	0
Faye	7.4	.58	1.61	6.0	204	199	9	42	− 4	8.2	.52	1.95	6.2	180	234	8	53	0
Whipple	7.5	.35	2.47	5.2	190	188	10	18	− 2	19	.30	5.0	9.3	113	271	6	24	+ 5
Ashbrook-Jackson	7.5	.40	2.31	5.3	349	2	13	352	− 2	14	.26	4.4	7.4	111	201	7	313	+ 7
Reinmuth 1	7.6	.49	1.98	5.7	9	121	8	130	+ 1	7.1	.49	1.89	5.5	352	156	9	148	− 1
Arend	7.8	.53	1.83	6.0	45	358	22	40	+15	8.0	.49	2.04	6.0	40	8	24	45	+15
Schaumasse	8.2	.71	1.20	6.9	52	86	12	138	+ 9	8.3	.65	1.42	6.7	41	104	24	142	+15
Wolf	8.4	.39	2.51	5.8	161	204	27	7	+ 8	7.4	.50	1.89	5.7	166	216	26	24	+ 6
Comas Solá	8.6	.58	1.78	6.6	40	63	13	102	+ 9	10	.49	2.34	6.8	46	76	20	119	+14

fected intermittently by the 3/5 resonance, at a period of 7.1 years; from 1889 to 1936, however, it was moving more under the influence of the 4/7 resonance, corresponding to a period of 6.8 years. *P*/Grigg-Skjellerup is alternately influenced by the 2/5 and 3/7 resonances; thus it could be regarded from a long-term viewpoint as governed by the 5/12 resonance.

Present orbital eccentricities range from 0.35 for *P*/Whipple to 0.84 for *P*/Encke, averaging 0.57. Five of the perihelion distances are less than 1 astronomical unit, and five exceed 2 astronomical units; the median value is 1.56, compared to 0.91 astronomical unit for comets as a whole. Orbits with short perihelion distances tend to have large eccentricities, so that the aphelia are in fact fairly close to Jupiter's orbit, ranging in distance from 4.1 to 6.9 astronomical units; for this reason the bodies are sometimes said to belong to the Jupiter family of comets.

All the comets move in direct orbits inclined at small angles to the ecliptic, and thus to the orbit of Jupiter; the maximum value of the inclination i is currently 31 degrees (for *P*/Giacobini-Zinner and *P*/Borrelly). We may also observe that the values of ω, the argument of perihelion, cluster around 0 and 180 degrees. Thus, when the comets are near aphelion, they are also near a node, so that they can physically pass very close to Jupiter. This point is brought out even more strongly if we consider the latitudes of perihelion, defined by arcsin (sin ω sin i). Only *P*/Arend has a latitude of perihelion numerically greater than 9 degrees, and it is because of its large perihelion latitude that this comet has been able to stay undisturbed at the 2/3 commensurability for so long. The same generalities hold also for the orbits at the 1725 epoch, even though many of the values of ω, for example, are considerably different. The orbital inclination of *P*/Brorsen then had an unprecedented value of 49 degrees, but with ω at 359 degrees the perihelion was almost exactly on the ecliptic.

The longitudes of the ascending node Ω are of little intrinsic interest, although the figures illustrate the well-known phenomenon whereby in a direct orbit the nodes regress with time. Sometimes i passes through zero, implying an instantaneous jump of 180 degrees in the line of nodes.

The distribution of longitudes of perihelion, defined by Ω + arctan (tan ω cos i), or approximately by $\Omega + \omega$ for small i, is curiously asymmetric. More than two values out of three lie in the semicircle 300–30–120 degrees. Precisely the same effect appears in the case of the asteroids (where the sample is much larger, with almost 1700 reliable orbits). The longitude of perihelion of Jupiter's orbit itself lies near the peak of the distribution. If we look instead at the longitudes of the proper perihelia of the asteroid orbits (that is, the perihelia are corrected for the secular perturbations due to Jupiter), the asymmetry is reduced to about 59 percent, and that beyond 50 percent can probably be attributed to simplifications made in the theory of secular perturbations. But it is hard to see that this would also be true of the comets on account of the close approaches to Jupiter. We may surmise that the asymmetry may have arisen because some of the comets may be fragments of an original comet that split (*20*), but such a conclusion defies proof. We could argue for a common origin for comets Borrelly and Daniel, but the similarity of the orbits could be due to chance. The longitudes of perihelion of the cometary orbits remain fairly stable, and in only ten instances do the values at the two epochs differ by more than 15 degrees. The two comets for which the difference is greater than 45 degrees, *P*/Brooks 2 and *P*/Wolf-Harrington, illustrate the phenomenon of apse-reversal, in which the perturbations by Jupiter caused the orbital eccentricity to pass through zero. The passage of comet Brooks 2 near Jupiter in 1886, 3 years before it was discovered, has been extensively studied (*21*). Our calculations indicate that comet Wolf-Harrington suffered a similar disturbance in 1842, but they are very tentative.

With reference to the comets of rather longer period, it used to be popular to speak of the Saturn, Uranus, and Neptune families, for cometary aphelia seemed to cluster around the orbits of these planets as well as that of Jupiter. The Neptune family, which includes Halley's comet, is particularly well defined. However, as several writers pointed out during the early years of this century (*22*), on account of the inclinations of the orbits, Neptune has a much smaller effect on the members of its "family" than does Jupiter. Russell (*23*) demonstrated that Jupiter has the most significant effect on almost all the periodic comets. *P*/Tempel-Tuttle and *P*/Halley travel in retrograde orbits, but they are nevertheless inclined at rather small angles to the ecliptic. Six of the remaining periodic comets of more than one appearance have orbits inclined at more than 40 degrees, but the tendency for ω to cluster around 0 and 180 degrees again prevails and prevents any of the latitudes of perihelion from exceeding 40 degrees.

Evolution of the Periodic Comets

The severe changes that the orbits of comets Brooks 2 and Wolf-Harrington have undergone illustrate the probable manner in which the periodic comets evolved. We may suppose the Jupiter family of comets to have originated from long-period comets having direct orbits of relatively low inclination, moderate-to-large eccentricity, and perihelion distance close to Jupiter's mean distance. Sooner or later a comet would pass near Jupiter, and the two bodies would then be moving virtually parallel to each other, so that the planet's influence on the comet would be extended over a long period of time (*24*). As often as not, the encounter would decrease the eccentricity, and at the next approach to Jupiter the influence would be more pronounced, since the motions of the bodies would be more closely matched. The eccentricity of the orbit might eventually pass through zero, so that the perihelion would come within Jupiter's orbit, and the comet might perhaps become visible from Earth. As the eccentricity in the inner orbit increased, the effect of Jupiter would become less important; for this reason there are few short-period comets having really large eccentricities and perihelion distances of less than 1 astronomical unit. We should certainly expect more periodic comets at greater perihelion distances—as great as well beyond the orbit of Jupiter.

None of the comets listed in Table 1 currently has a perihelion distance greater than 2.6 astronomical units (half the mean distance of Jupiter), and only three short-period comets have ever been observed in orbits with such large perihelion distances. The highly unusual *P*/Schwassmann-Wachmann 1, which does not pass within 5.5 astronomical units of Sun, represents an earlier stage in the evolution of the Jupiter family of comets; and *P*/Oterma, which had a perihelion distance of 3.4 astronomical units when it was observed, now has a similar orbit. The recently discovered comet van Houten has a perihelion distance of 3.9 astronomical units and eccentricity of 0.37 (*3*). In addition to *P*/Brooks 2 and *P*/Wolf-Harrington, five of the objects in Table 1 (comets Kopff, Schwassmann-Wachmann 2, Holmes, Whipple, and Ashbrook-Jackson) formerly had large perihelion distances and rather small eccentricities, although no apse-reversal took place during the period covered by the calculations.

It would be foolhardy to suppose that these comets are thus relatively new, for one must only consider *P*/Lexell to see that the perihelion distance may change in either direction. After 1982 the perihelion distance of *P*/Whipple will increase again, to 3.1 astronomical units. Tracing the motions of the periodic comets for a few centuries does not prove which ones are new, but if the computations are made for a similar period of time in the future one may perhaps find that a smaller number of perihelion distances increase again. Supplementary evidence might be obtained from photometric observations. It could be argued, for example, that comet Schwassmann-Wachmann 1 has never been much nearer Sun than it comes now, or it would not exhibit such violent changes in physical appearance. Since the behavior of comet Holmes in 1892 was rather similar, we could presume that it too is a newcomer to the inner part of the solar system. The indications from spectroscopy are not so conclusive, and it is unfortunate that most periodic comets are too faint for satisfactory spectroscopic observations. That the spectrum of *P*/Holmes is completely continuous supports the hypothesis that this is a new comet; in the case of *P*/Encke, the spectrum shows no continuum whatsoever, and, if this comet is indeed the parent of the Taurid meteor streams (*25*), then it is an old comet, the orbit of which has remained essentially unchanged for at least several thousand years. But it is difficult to see why comets Brorsen and Pons-Winnecke, which also have had rather small perihelion distances for several centuries, should show such intense continua.

It has often been remarked that several of the periodic comets have aphelion distances smaller than Jupiter's perihelion distance, and that this situation could not arise if they evolved in the manner I have indicated. There are at present six such instances among the comets of more than one appearance, although only two of them (*P*/Encke and *P*/Tempel 2) have consistently had their aphelia inside Jupiter's perihelion for the last three centuries. It is certainly possible to obtain such an orbit, even if the perturbations by the inner planets are ignored. Jupiter alone was responsible for the aphelion distance of 4.5 astronomical units for comet Oterma. Whether the present orbit of Encke's comet, with an aphelion distance smaller by 0.85 astronomical unit than Jupiter's perihelion distance, could have evolved in the absence of nongravitational effects must be considered an open question.

The first serious attempt to study the origin of the periodic comets was made in 1893 by H. A. Newton (*26*). His conclusions were based on the assumption that comets, coming in randomly in parabolic orbits, made just one close approach to Jupiter. Obviously there would be further encounters, and the chances of these increase as the perturbations decrease the periods of the comets. The manner in which the semimajor axes are diffused has been investigated in greater detail by van Woerkom and by Shteins (*27*), the latter including a term to allow for the disintegration of comets. The diffusion mechanism depends little on whether we follow Oort in envisaging the source of comets in a vast cloud surrounding the solar system, or whether we subscribe to Lyttleton's views that comets arise by accretion (*28*).

Newton, van Woerkom, and Shteins have been unable to explain the complete absence of Jupiter-family comets having retrograde orbits. For this reason Vsekhsvyatsky rejects the notion that short-period comets evolve from long-period ones; he has advanced the theory (as did Lagrange before him) that they originate by some kind of volcanic eruption from Jupiter (*29*). This idea cannot be seriously entertained, however, for it would then become impossible to explain the existence of long-period comets, most of which can never pass anywhere near Jupiter.

We must presume that the number of short-period comets is about the same at any instant in the history of the solar system. As we have seen, the number of comets having perihelion distances of less than half Jupiter's mean distance is augmented by perhaps 7 percent per century. It is difficult to say whether the steady state is principally maintained by the expulsion of comets to the outskirts of the system, or by the dissolution of comets in the inner regions. We may deduce that, on the average, a comet can survive in a short-period orbit for at least 1400 years, making more than 200 revolutions about Sun. Whipple has attempted to explain the secular changes (if they exist) in the periods of comets by the ejection of material by sublimation from a rotating nucleus of icy conglomerates (*30*). For Encke's comet, he found a lower limit to the mass-loss to be 0.2 percent per revolution, implying a lifetime of at least 2000 years, and a comparable figure comes from the association with Taurid meteors. At the opposite extreme, however, Whipple has inferred by literal interpretation of Vsekhsvyatsky's magnitudes that *P*/Encke is losing mass at a much greater rate, and that it will cease to exist by the end of this century (*11*); in fact, some 60 percent of the known periodic comets should have burned out by the year 2000!

Many of the most-persistent meteor streams have no known cometary parent, presumably because any comet that was associated no longer exists. Hoffmeister (*31*) has correlated some of these streams with asteroids of the Apollo type, which have small perihelion distances and are only visible when near Earth; Öpik (*32*) has suggested that these asteroids may in fact be extinct cometary nuclei. Several of the periodic comets show little evidence of cometary activity: comets Arend-Rigaux and Neujmin 1 were completely asteroidal in appearance at their more-recent returns (*33*), and they would never have been classed as comets at all if they had not seemed diffuse when first discovered. Recent determinations of the radii of the nuclei of several periodic comets (*34*) are not inconsistent with those of Apollo-type asteroids.

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Citation Indexing and Evaluation of Scientific Papers

The spread of influence in populations of scientific papers may become a subject for quantitative analysis.

J. Margolis

As a result of the recent expansion of scientific literature, more time and effort are being devoted to the selection of what is to be read than to the actual reading. To cope with the demand there has been a corresponding growth of abstracting and indexing services as well as of sophisticated computer-based systems for information storage and retrieval such as the "Medlars" development (*1*). Against this rapidly shifting background it is almost impossible to say what is the prevalent attitude of users toward scientific publications, but presumably most readers still try first to ascertain the nature of an article's contents by reference to its author, title, or other subject descriptors.

The use of the bibliography as a point of departure is a relatively new approach, which became practicable only with the compilation of citation indexes (*2*). It is self-evident that the contents of an article determine to what papers the article will refer. Perhaps less obvious is the fact that in some respects the bibliography appended to an article specifies uniquely, if indirectly, its subject (*3*). The practice of appraising a paper by noting the references it cites is probably quite common. When a busy research worker scans the current periodicals he may be able to decide at once from the list of references whether an article with an interesting title is worth reading. He may, for example, be inclined to reject a paper that does not mention some important contributions on the subject. More generally, each item on the list provides a clue, and the total "spectrum" of such clues will often identify the theme. For those who can read the code, this identification is an act of instant and effortless recognition—effortless, that is, compared with evaluation of any part of the contents. However, this approach can be useful only to the reader who is already familiar with the literature, and, in any case, it depends on finding the article first, either by chance or by way of the existing subject-oriented information channels.

The appearance of a comprehensive *Science Citation Index* (*4*) has made it possible for the first time to systematize this procedure for general use. The structure and operation of the *Index* have been described in detail elsewhere (*2, 5–7*). In essence, it is produced by listing all the items cited in papers (sources) in a multidisciplinary selection of scientific, technical, and medical periodicals (613 journals in 1961 and more than 1500 in 1966). The items are in the form of line entries, arranged alphabetically by the name of the first author, followed by the year, name of the journal, volume, page, and certain other coded information. Under each citation are listed all the citing (source) articles, identified in a similar manner. The *Index* is produced quarterly (with a cumulative issue at the end of each year) and lists only the source papers published in the journals being processed at the time. No such restrictions apply to the cited items. Anything that may appear in the list of references, from "personal communications" to citations of Lewis Carroll or Confucius, is a legitimate entry.

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