PHYSICAL AGING IN COMETS

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ABSTRACT. Recent evidence suggests that comets formed at low temperatures (≤ 25 K) and that, while the interiors have not been considerably altered since formation, the outer layers have undergone substantial modification. Comets exhibit a wide range of physical characteristics, some of which may be attributed to systematic physical differences between comets making their first close approach to the Sun from the Oort cloud (new comets) and those having made many approaches (old comets). These differences may reflect either primordial differences between two populations or the differences may be a manifestation of aging processes. There are many processes that might be responsible for causing aging in comets. These include: (i) radiation damage in the upper layers of the nucleus during the long residences in the Oort cloud, (ii) processing from heating and collisions within the Oort cloud, (iii) loss of highly volatile species from the nucleus on the first passage through the inner Solar System, (iv) buildup of a dusty mantle, which can eventually prohibit further sublimation, and (v) a change in the porosity, and hence the thermal properties of the nucleus. Although Oort's (1950) original work on the comet cloud *required* that new comets fade after their first close passage, past searches for evidence of aging in comets have produced conflicting results, partly due to a lack of systematic data sets. An understanding of the evolutionary processes of comet nuclei that give rise to compositional or physical differences between 'fresh' Oort cloud comets and thermally processed periodic comets will improve our knowledge of the possibly primordial comet composition and therefore conditions in the early Solar System. Recent observations suggest that there are distinct differences between the two groups with respect to intrinsic brightness and rate of change of activity as a function of distance.

1. Introduction

One of the principal goals of planetary science is to acquire an understanding of the chemical and physical processes occurring during the formation of the Solar System. All Solar System objects are formed from the interstellar medium, yet most material within the inner Solar System has been thoroughly processed and preserves no record of the conditions in the protoplanetary nebula. The degree to which the material has been

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processed depends upon the formation/condensation location and the orbital evolution. Comets, however, may still preserve a chemical record of their formation, since it is believed that they are relatively unprocessed bodies, although all dynamical information concerning cometary formation locations has been completely destroyed due to orbit randomization from stellar and planetary perturbations in the Oort cloud (Weissman, 1982). The study of cometary compositions will ultimately lead to a better understanding of cometary formation conditions in the early Solar System and to conclusions of how well cometary dust represents unprocessed interstellar medium (ISM) material (Greenberg, 1987). Comets are not completely unprocessed bodies; some appear to show very little activity due to the apparent loss of volatile material, whereas others appear to be extremely active over a large range of distances. In order to understand the relationship between the past conditions in the protosolar nebula and the present state of the cometary nucleus, it is very important to address the question of aging in cometary nuclei, and to understand the processes that will physically and chemically alter the nucleus as a function of time. In particular, searching for differences between dynamical classes of comets, that may be attributed to aging may provide insight into the primordial cometary composition.

The discussion of all processes that will alter the cometary nucleus and the observational evidence for these processes is an extremely large topic, which will be addressed in part by many of the papers in this volume. This review will therefore concentrate on discussing the evidence for systematic differences between two classes of comets: the periodic comets, which have spent considerable time within the inner Solar System, and the dynamically new, or "Oort cloud," comets, which may be making their first passage through the inner Solar System. The reader is referred to the chapter by Kresák (this volume) for a discussion of the evidence for aging in short-period comets and to several papers addressing the question concerning the evolution of comets into asteroids (Marsden, 1970; Kresák, 1979; Degewij and Tedesco, 1982; Rickman, 1985; Hartmann et al., 1987; Weissman et al., 1989).

2. Is Aging Expected?

Whipple's (1950) icy conglomerate model for cometary nuclei postulated that comets are mixtures of dust and water ice. When close to the Sun, dust particles are entrained in the sublimating ices, and sunlight scattered from the dust gives rise to the characteristic cometary comae and tails. Although there had been abundant indirect evidence for the validity of the Whipple model, the model wasn't completely verified until the 1986 P/Halley spacecraft encounters. Whereas the essential correctness of the Whipple theory has long been accepted, there has been continued debate on the question of whether activity in some comets is controlled by the sublimation of ices more volatile than H_2O. This question is intimately related to the discussion of aging in cometary nuclei.

2.1. Low-Temperature Formation

There are numerous arguments that make aging processes very likely for comets. Although the exact formation locations for comets are unknown, recent observational evidence indicates very low condensation temperatures. In the first observations of gaseous neutral water molecules in a comet, Mumma et al. (1986) have measured the ortho-para ratio for water in Comet P/Halley. The revised values of 2.3 ± 0.1 (pre-perihelion) and 2.2 ± 0.1 (post-perihelion) reported by Mumma et al. (1988) imply nuclear spin temperatures of ~25 K. This was essentially constant over a period of several months for two different nuclear regions, suggesting that the temperature is a property of the nucleus as a whole. Mumma et al. (1987, 1990) show that the ortho-para ratio is a cosmogonic invariant, i.e., that collisions in the coma cannot affect the ratio, and that condensation and sublimation processes cannot alter the ratio. Mumma et al. conclude, therefore, that the nuclear spin temperature derived for P/Halley suggests that the nuclear ices may have formed in cold molecular clouds before accretion into the nucleus.

The detection of S_2 in Comet IRAS-Araki-Alcock by A'Hearn et al. (1983) has been used by many to likewise infer that comets formed at low temperatures. Greenberg et al.(1986), Grim and Greenberg (1987), and references therein have discussed the problem and shown that S_2 must be a parent molecule, because of its rapid rate of photodissociation, and furthermore that the compound must be produced by photolysis of S-containing compounds in interstellar grains, since it is unlikely to be produced by condensation processes (A'Hearn and Feldman, 1984). These grains cannot have been heated much above 25 K and still be present, thus implying low-temperature formation conditions. The only problem with this scenario is that S_2 has been detected only in this one comet, so it may be premature to consider that this is a general demonstration of the low-temperature formation conditions of comets.

Laboratory studies by Bar-Nun and Prialnik (1989) of trapped gases in amorphous water ice likewise have inferred a low formation temperature for P/Halley. In order to trap the observed 3.5% CO (Krankowsky et al., 1986) in the water ice, they calculate that the comet must have formed at temperatures around 48 ± 5 K. Finally, Greenberg (1987) discusses the similarities of the cometary grain material observed in P/Halley with dust in the ISM, in particular, with respect to the small submillimeter grains detected, the low grain albedos and presence of non-volatile organics, among other things. The character of the interstellar grains would not be preserved within the cometary nucleus if comets did not form at relatively low temperatures.

Comets that pass through the inner Solar System certainly will be heated above these low formation temperatures; therefore it is reasonable to expect that there will be physical processing of the nucleus due to thermal effects. Additionally, if comets formed at low temperatures with a significant fraction of volatile ices such as CO, CO_2, CH_2O and NH_3, then these would be preserved when the comets are at the low Oort cloud temperatures, but not necessarily when the comets are close to the Sun. Thus, it seems reasonable that it might be possible to detect observational differences or aging (e.g., physical, behavioral or compositional) effects between comets of different dynamical classes, depending on the length of time spent within the inner Solar System.

2.2. IRRADIATION EFFECTS IN THE OORT CLOUD

Before discussing the differences that might be expected between dynamically new and old comets close to the Sun, it is necessary to consider those processes that may alter the nucleus while it is still far from the Sun. For example, during a comet's residence in the Oort cloud, say, on time scales of 10^9 years, the surface layers (the upper few meters) suffer radiation damage from energetic galactic cosmic rays and ultraviolet (UV) photons, which can produce both low-albedo non-volatile residues (forming a crust) and highly

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volatile molecules (Moore et al., 1983; Johnson et al., 1987; see also the chapter by Strazzulla and Johnson in this volume). Subsequent warming on the first close solar passage would cause rapid sublimation of these volatiles from the crust, resulting in an excess of activity. The exact nature and amount of the activity will depend on the concentration of the volatile species in comparison to H_2O (Sandford and Allamandola, 1988), in addition to the thickness and uniformity of the crust. In fact, the loss of volatiles at large distances inhibited by a crust may be the cause of outburst activity frequently seen in comets. Irradiation damage to the comet nucleus is not restricted only to the time during which the comet resides in the Oort cloud. It is expected that UV photolysis will chemically alter grain mantles prior to their incorporation into the nucleus (Greenberg, 1977, 1982; d'Hendecourt et al., 1986). However, this process would not be expected to create differences between new and old comets, whereas the irradiation damage of the surface layers of the nucleus while in the Oort cloud may create excess activity during the first passage of new comets, as pointed out by Donn (1976) and Whipple (1977), who used the term "volatile frosting."

More recently, Stern and Shull (1988) have discussed the effects of heating Oort cloud comet nuclei by novae and supernovae and passing stars. They conclude that over the age of the Solar System, 6% to 20% of the mass of all Oort cloud comets would have been heated from their calculated ambient temperature of 4.4 K to at least 16 K and some to 30 K by the passage of luminous (O and B) stars through the Oort cloud. Events such as supernovae and novae may heat a thin layer (< 1 m) to higher temperatures (45 to 60 K). Whereas the heating will certainly alter the pristine nature of the comet nuclei, only the processing of a thin outer layer by novae and supernovae might cause a distinction between the old comets and the new comets on their first passage. The same may be inferred from Stern's (1988) modelling, which indicates that gardening due to collisions within the Oort cloud will produce a surface layer turnover to at least several centimeters in depth and perhaps up to several meters. In contrast, much of the altered surface layers may be removed due to erosion from the interstellar medium (Stern, 1989a).

2.3. DYNAMICAL EVOLUTION AND CHEMICAL CONSIDERATIONS

The question of aging initially arose when Oort (1950) and Oort and Schmidt (1951) deduced the existence of the Oort cloud (between 5×10^4 and 1.5×10^5 AU), and, from their observations, concluded that new comets first coming into the inner Solar System must subsequently fade in brightness due to rapid sublimation of highly volatile ices not normally seen in the short-period comets. This assertion that the comets must fade was somewhat ad hoc; however, theoretical calculations by Bailey (1985) support the conclusion requiring strong fading. Since Oort's original work on the subject, Marsden and Sekanina (1973) have reexamined the distribution of original comet orbits (by removing the effects of planetary perturbations) and suggested that the size of the Oort cloud is much smaller than previously believed by Oort. As a consequence of this, Weissman (1986) maintains that comets coming into the observable region may be perturbed by a variety of galactic sources (Weissman, 1990) and thus will diffuse slowly into the inner Solar System. Hence, there is no reason to expect a higher volatile content in the new comets compared with the old comets. Duncan et al. (1988) have gone further to suggest from results of numerical simulations that the short-period comets *cannot* have the Oort cloud as a source region. A low-inclination Kuiper belt of comets beyond Neptune's

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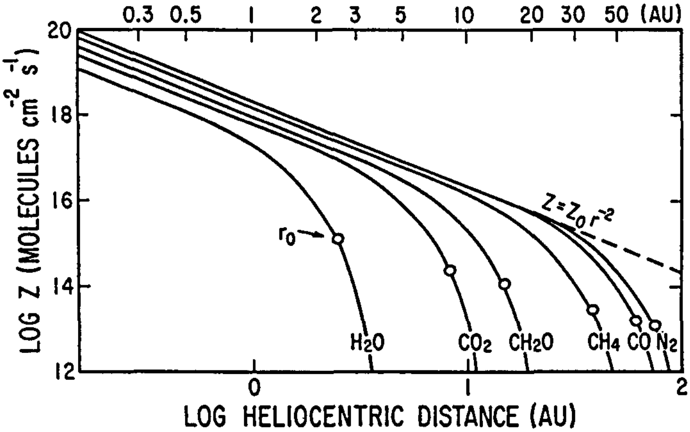

Figure 1. Vaporization rate, in molecules·cm^{-2}·s^{-1}, for various ices as a function of heliocentric distance, assuming a steady-state rotating nucleus. This is Figure 1 from Delsemme (1982).

orbit, which represent remnants of the planetary accretion process, is suggested as a more likely source. The slow diffusion of comets into the inner Solar System makes the observations of aging effects more difficult, and the presence of different source regions makes the interpretation of any observed differences very difficult.

Nevertheless, in both cases, it is likely that there may be observational differences between comets that have spent little or no time in the inner Solar System and those that have. Delsemme (1982) has shown that for a variety of cosmogonically important ices, the vapor pressures and sublimation rates are orders of magnitude different. From his figure (reproduced here as Figure 1), it is clear that differences between comets could be easily distinguished by observing the heliocentric distance, *R*, at which a coma is produced by sublimation of simple ices. The common consensus (first proposed by Delsemme and Swings, 1952) has been that many of the more volatile ices are bound within H_2O-ice clathrates, where the H_2O ice controls the rate of sublimation. Effects due to different volatile contents would therefore not necessarily be apparent. Sandford and Allamandola (1988) have shown in laboratory experiments that the presence of CO in H_2O:CO clathrates will substantially increase the H_2O volatility at low temperatures between 30 to 65 K, 125 to 150 K, and 150 to 175 K (corresponding to distances beyond Uranus, near 4 AU and 3 AU, respectively, for low-albedo materials). Therefore, even water-ice dominated bodies may become active at large heliocentric distances. For low-temperature amorphous ices (< 140 K), the impurities within the H_2O ice must be > 30% before the species more volatile than the H_2O will control the sublimation.

2.4. The Inner Solar System—Mantle and Crust Development

Once comets enter the inner Solar System, the thermal effects due to heating from the Sun will be dominant over other factors. Only a brief mention will be made (for completeness) of these aging processes. Once the nucleus temperatures rise above ~140 K, the water ice will undergo an exothermic phase transition from amorphous to crystalline ice (Patashnick et al., 1974; Klinger, 1980, 1981; Smoluchowski, 1985; Prialnik and Bar-Nun, 1987), which may be observable as outbursts or excess activity beyond the distance where H_2O sublimation is important (~6 AU for P/Halley; Wyckoff et al., 1985; Meech et al., 1986). As a comet loses its volatiles, it is expected that the nucleus will build up a mantle of dusty residue from large particles not carried away during sublimation and that this crust will inhibit or entirely cut off sublimation from the nucleus (Mendis and Brin, 1977, 1978; Brin and Mendis, 1979; Fanale and Salvail, 1984; Horanyi et al., 1984). As loss of volatiles proceeds, not only will the surface layers become depleted in volatiles, but densification will occur as vapors condense in cooler subsurface layers (Smoluchowski, 1981, 1985, 1989). This may create chemical differentiation in an initially undifferentiated nucleus (Houpis et al., 1985; Smoluchowski, 1986; Fanale and Salvail, 1987, 1989), possibly explaining excess activity in new comets.

From the previous discussion, it should be apparent that the question of aging is extremely complex—there are many processes that may alter cometary nuclei. For a more comprehensive discussion of these processes, both before, during, and after nucleus formation, the reader is referred to Weissman and Stern (1989). Whipple (1989) provides a nice summary of how these effects might be detected observationally. Although it is very unlikely that any comets are pristine in nature, as pointed out by these authors, there is much observational evidence that many comets still contain a large fraction of their original volatile constituents. The question of aging has been discussed at length in the literature by various authors, but has only recently been addressed observationally in a systematic manner. The rest of this review will discuss the observational evidence related to aging processes.

3. Past Searches for Evidence for Aging

Just as the precise definition of what constitutes aging in comets and whether it is expected is not a simple topic, the past investigations to search for these possible compositional differences or aging effects have produced conflicting results.

3.1. Orbital Considerations—Fading

As mentioned in the previous section, comets may slowly diffuse into the inner Solar System, which suggests that new comets are not necessarily expected to have a large abundance of highly volatile materials. Marsden et al. (1978), however, reported that the original orbits for 200 comets *did* suggest cometary fading after the first close solar passage. They divided the comet orbits into two accuracy classes that depend on (i) the mean error of $1/a$, the reciprocal of the semi-major axis, (ii) the time span of the observations determining the orbit, and (iii) the number of planets whose perturbations are taken into account. In the class for which the orbits were the most accurately known, class

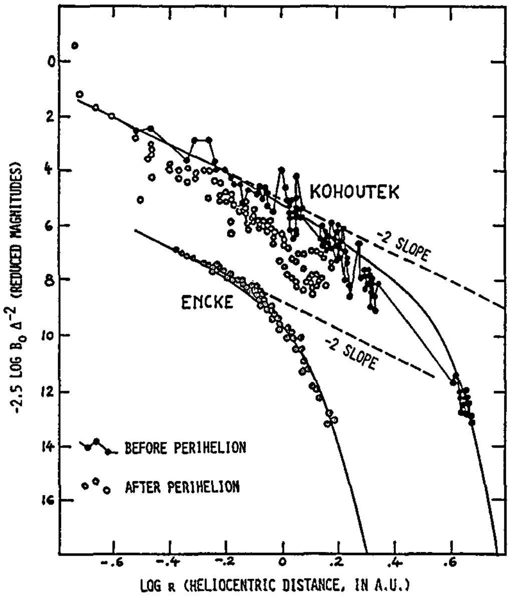

Figure 2. Light curves of comets P/Encke and Kohoutek as a function of distance. The closed circles for Kohoutek represent pre-perihelion measurements, and the open circles post-perihelion ones. The figure shows the post-perihelion fading of the comet. This is reproduced from Figure 2 of Delsemme (1975).

I, as many as 55% of the comets were "new" ($(1/a)_{orig}$ < 100 [10^{-6} AU^{-1}]), whereas in class II, the fraction of new comets fell to about 21%. The larger proportion of old comets in class II, where the orbits were less accurate, was interpreted as evidence for fading by Marsden et al. (1978), since if a comet fades substantially after its first passage through the inner Solar System, it will be observed over a smaller portion of its orbit on successive passages, and hence have a greater probability of inclusion in class II. A good example of this type of fading in a new comet is shown by the light curve of Comet Kohoutek (1973 XII), shown in Figure 2 (from Delsemme, 1975), which shows a post-perihelion light curve substantially fainter than the pre-perihelion leg. In contrast, periodic comet light curves can be either brighter post-perihelion (the usual case) or fainter. Post-perihelion brightening may be the result of the penetration of the thermal heat wave through a low-conductivity insulating mantle. An example of this behavior in P/Tempel 2 is reproduced in Figure 3 (after Sekanina, 1979).

Marsden et al. (1973) have also considered the variation of the nongravitational forces with heliocentric distance and found that the orbital solutions are best fit when considering vaporization from H_2O ice. However, as Weissman (1979) discusses, very few nongravitational solutions exist for long-period comets, since the solutions are usually

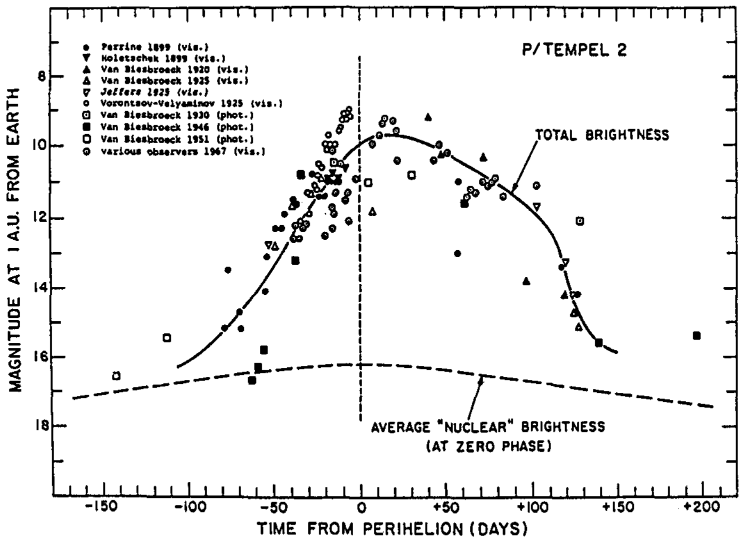

Figure 3. Light curve of Comet P/Tempel 2 as a function of time from perihelion in days. The curve shows the post-perihelion brightening (as opposed to the fading seen for Kohoutek). The data have been compiled from a variety of sources in this figure reproduced with permission from Sekanina (1979), Academic Press.

obtained by linking several apparitions together. Therefore, the nongravitational solutions cannot really be used as an aging distinction between new and old comets.

Another way to consider cometary fading is to compare the largest distance at which a comet is observed as a function of dynamical age. Distance was chosen as less likely to be influenced by selection effects than would be magnitude estimates, especially for the older data. Selection effects will still almost certainly be present, but a careful examination of all possible effects has shown that they should equally affect both the old and the new dynamical classes. In Figure 4, the distances at the farthest known observations are plotted versus date for > 100 class I comets (in *nearly parabolic orbits*). The values of R [AU] are computed from the dates of the extreme observations found in Kronk (1984), using the orbital data from Marsden et al. (1978) and Everhart and Marsden (1983, 1987). The vertical bars on the data represent 0.1 times the perihelion distance, q, in AU. The data for the new comets [$(1/a)_{orig} < 100$] are presented in the top panel, and the data for the old comets [$(1/a)_{orig} > 100$] in the bottom panel. The figure clearly shows a difference between the dynamically old and new populations. The scatter in both groups is due, in part, to intrinsic brightness differences among the comets and also to selection effects. The effect of improved instrumentation and techniques is seen particularly well in the top panel, where there is a general increase with time in the distance of the faintest observations. It is *significant* that this trend is less conspicuous in the bottom panel. The fact that there were a number of old comets (between 1960 and 1980) that were observed out to distances of only

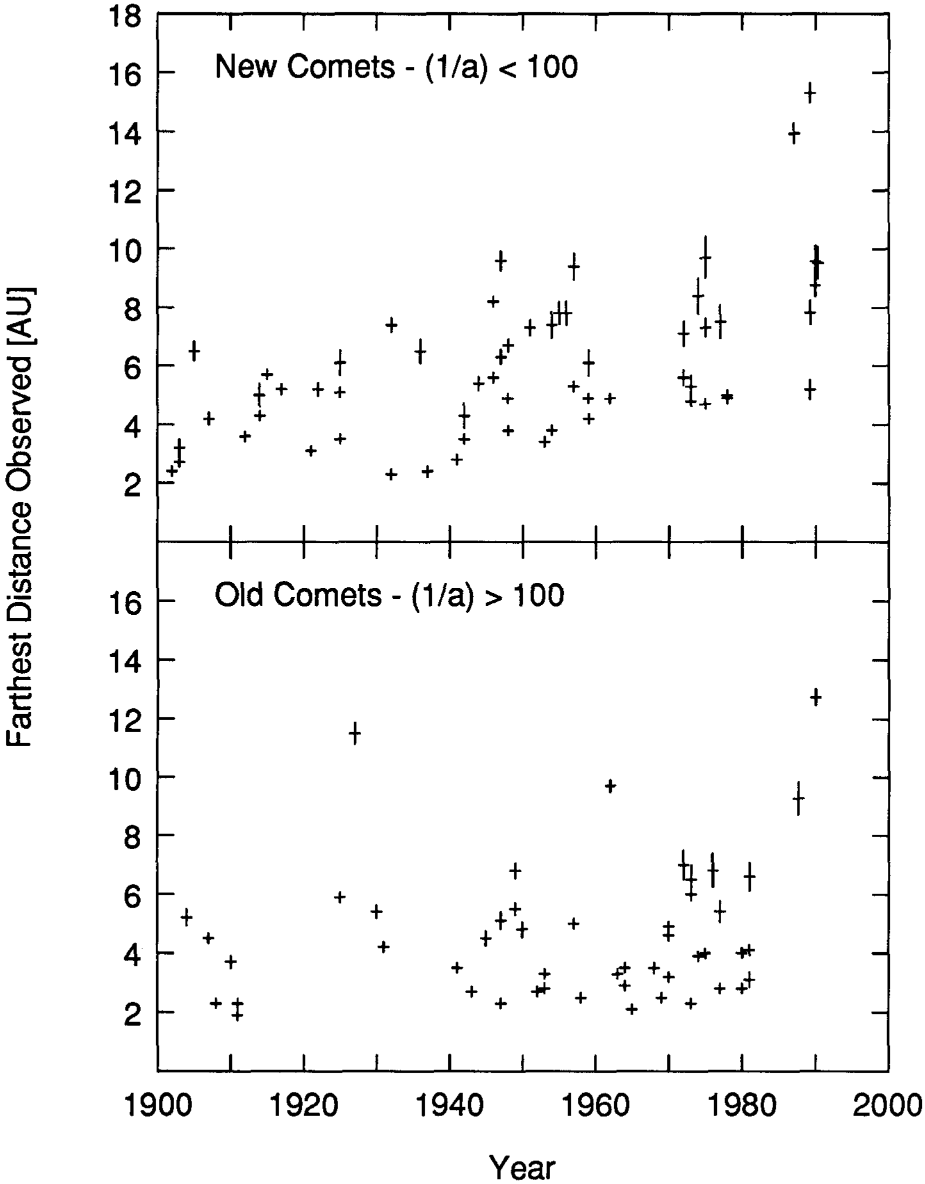

Figure 4. Farthest distance, R, at which a comet was observed versus date (years) for ~100 comets with nearly parabolic orbits. The upper panel plots the dynamically new comets for which $(1/a)_{orig}$ < 100; the lower panel shows the old comets for which $1/a_{orig}$ > 100. The quantity $(1/a)_{orig}$ is in units of 10^{-6} AU. The vertical bars on the data represent 0.1 times the perihelion distance. See text for discussion.

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2 to 4 AU, and the absence of such a group in the new comets, suggests that the old comets tend to be intrinsically fainter.

There is also a pronounced difference in the number of large-q comets between the two panels: there are many more large-q comets in the new group. This was noted by Marsden and Sekanina (1973), who stated that for large q, the Oort effect is much more pronounced. They interpret this as evidence for substantial fading, on second and subsequent passages, and since large-q comets never approach very close to the Sun, it may be easier to fade to a brightness that is below the detection threshold. Furthermore, the large-q comets appear to be intrinsically brighter than the low-q comets, in that they are typically observed to larger heliocentric distances. This is due, in part, to the fact that by definition they will not ever approach the Sun more closely than q, which is large; therefore we are sampling only the brightest members of the population.

3.2. ACTIVITY AT LARGE R—ONSET AND CESSATION OF ACTIVITY

There are many references in the literature that suggest that new comets are intrinsically more active at large distances from the Sun than are the periodic comets. Barnard (1890) was one of the first to realize the importance of studying comets by comparing their behavior over a wide range of distances when he noted that "observers as a general rule neglect comets as soon as they become faint or difficult." Roemer (1962) maintained that there was no difference between nearly parabolic comets and short-period comets with respect to the brightness variation as a function of distance, stating that examples of comets that brightened either rapidly or slowly as a function of R could be found in both classes of comets. Yet, like Barnard, Roemer realized that this might be due to the lack of observations at large R (and interest in getting them). In fact, if one looks at the data in the literature and compares all comets that have been reported to exhibit activity at large distances (> 5 to 6 AU), it is apparent that a large fraction of them are dynamically new comets, and none are periodic comets, with the exception of P/Schwassmann-Wachmann 1 and P/Halley (and this one only recently).

Table 1 presents a subset of the nearly parabolic comets (both old and new) shown in Figure 4 and the few periodic comets that have reported activity at large heliocentric distances. The name and the designation are given for each comet in column 1 of the table, in addition to the years during which the comet was observed (the most recent apparition only for the periodic comets). The approximate date of perihelion passage, T (yr), and the perihelion distance, q (in AU), as obtained from Marsden (1986), are listed in columns 2 and 3. The values of $(1/a)_{orig}$ from Marsden et al. (1978), Everhart and Marsden (1983, 1987), and Marsden (private communication) are listed in column 4. An "SP" in this column indicates that the comet is periodic, with a period < 200 years. In column 5, an estimate of the distance of the formation of the tail is given, based on the dynamical analysis of Sekanina (1975) and the descriptions found in Kronk (1984). Sekanina's tail formation estimates are enclosed in parentheses in the table because they are computed, as opposed to observed, quantities. Finally, in the last column are additional comments (obtained from Kronk, 1984, and the author's present research) that relate to the activity. Although the table includes both new and old comets, nearly 70% of the listed comets are new. The most obvious characteristic common to all of the comets is that they possess comae and, in many cases, tails, out to very large distances. Roemer (1962), Belton (1965), and Sekanina (1975), among others, have all commented upon the fact that the dust

Table 1. Characteristics of Comets Active at Large Distances

Comet	T (years)	q (AU)	$(1/a)_{orig}$ (10^{-6} AU)	Tail	Comments
Kohoutek (1973 XII) (1973–1974)	1973.99	0.142	20	< 4.2 AU	Found ~5.1 AU, mag. 16 with coma. Last obs. at 4.8 AU, near mag. 22.
Halley (1986 III) (1982–present)	1986.11	0.587	SP	< 2.0 AU	Activity began at 6 AU and ended near 8.5 AU (West and Jørgensen, 1989).
Morehouse (1908 III) (1908–1909)	1908.98	0.945	174	> 2.1 AU	CO^+-dominated spectrum.
Mellish (1915 II) (1915–1916)	1915.54	1.005	75	> 2.6 AU	Mag. ~16 at 5.7 AU. Nucleus split in 1916. Fan-shaped tail.
Jones (1946 VI) (1946–1948)	1946.82	1.136	44	~7.7 AU	Last obs. at 8.2 AU.
Wilson (1987 VII) (1986–1989)	1987.30	1.200	30		Discovered at R = 3.6 AU with bright coma. Split between 8/87 and 2/88.
Ikeya-Seki (1968 I) (1967–1969)	1968.15	1.697	842	> 2.1 AU	Last obs. ~6.7 AU w/coma.
Pajdusakova-Mrkos (1948 V) (1948–1950)	1948.37	2.107	34	> 5.6 AU	Last obs. ~6.7 AU w/coma.
Humason (1962 VIII) (1961–1965)	1962.94	2.133	4935	> 5.6 AU	CO^+-dominated spectrum. Ion tail at 3.1 AU. Outbursts near 6 AU. Last obs. ~9.7 AU w/coma.
Baade (1922 II) (1922–1924)	1922.82	2.259	21	> 5.2 AU	

Table 1. (continued)

Comet	T (years)	q (AU)	$(1/a)_{orig}$ (10^{-6} AU)	Tail	Comments
Geddes (1932 VI) (1931–1934)	1932.72	2.314	45	(5.5 AU)	Last obs. ~7.4 AU w/coma.
Wirtanen (1949 I) (1948–1951)	1949.33	2.517	498	> 3.9 AU	Last obs. at 6.8 AU.
Minkowski (1951 I) (1950–1953)	1951.04	2.572	37	(2.6-5.5 AU)	Last obs. ~7.3 AU w/coma 20 arcsec across.
Churyumov-Solodovnikov (1986 IX) (1986–present)	1986.35	2.642	646		Coma visible at 9.5 AU.
Shoemaker† (1985 XII) (1984–present)	1985.68	2.696	487	> 6 AU	Extensive coma and tail at 4.9 and 6 AU. Coma at 12.7 AU.
Lovas (1975 VIII) (1974–1977)	1975.64	3.011	36	> 4.8 AU	Last obs. ~7.3 AU. Tail faint and broad.
Wirtanen (1947 VIII) (1948–1950)	1947.67	3.261	34	> 4.9 AU	Last obs. at 9.6 AU.
Gehrels (1971 I) (1972–1973)	1971.02	3.277	1582	~7.4 AU	Never brighter than 16 mag.
Thomas (1969 I) (1968–1971)	1969.03	3.316	1502	(3.3 AU)	Last obs. ~8 AU, diffuse.
Cernis (1983 XII) (1983–present)	1983.55	3.318	78		Coma at 9, 11, 13, 14.1, and 15.3 AU.
Jensen-Shoemaker ($1987g_1$) (1987–present)	1988.05	3.334	-4		Highly structured tail at 5.2 AU.

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Table 1. (continued)

Comet	T (years)	q (AU)	$(1/a)_{orig}$ (10^{-6} AU)	Tail	Comments
Kopff (1905 IV) (1904–1907)	1905.79	3.340	28	> 3.6 AU	Last obs. ~6.4 AU diffuse, mag. ~16. Split in 12/1905.
Bowell (1982 I) (1980–1987)	1982.19	3.364	30	(12 AU)	a§~300 μm, low velocity. Narrow tail, obs. ~14 AU.
Torres (1987 V) (1987–present)	1987.27	3.624	45		Spiral structure in coma, 3.7 to 8.8 AU.
Stearns (1927 IV) (1927–1931)	1927.22	3.684	623	6 AU (3.9-5.6 AU) narrow	Coma to >11 AU. Last obs. 11.5 AU. C_2 obs. near 4 AU (van Biesbroeck, 1927b).
Baade (1955 VI) (1954–1957)	1955.61	3.870	42	> 5 AU (4-12 AU) (12-30? AU)	a > 100 μm, low velocity. Last obs. ~7.8 AU. Diffuse, narrow tail.
Hartley (1985 XVI) (1984–1988)	1985.74	4.000	35		Obs. at 8.5 AU, diffuse.
Van Biesbroeck (1936 I) (1935–1938)	1936.36	4.043	19	(~4 AU)	Last obs. ~6.5 AU, diffuse.
Haro-Chavira (1956 I) (1954–1958)	1956.07	4.077	39	> 5 AU (6-15? AU)	a > 100 μm, low velocity. Narrow tail, 7 AU diffuse.
Shajn-Comas-Solá (1925 VI) (1925–1927)	1925.68	4.181	35	None	Last obs. at 6 AU, diffuse. Total mag. near 16.
Humason (1959 X) (1960–1961)	1959.94	4.267	40	> 4.6 AU	Last obs. ~6.1 AU, diffuse. Narrow tail.
Sandage (1972 IX) (1972–1974)	1972.87	4.276	69	> 4.5 AU (4-8 AU)	Last obs. ~7.1 AU, diffuse.

Table 1. (continued)

Comet	T (years)	q (AU)	$(1/a)_{orig}$ (10^{-6} AU)	Tail	Comments
Wirtanen (1957 VI) (1956–1960)	1957.67	4.447	17	> 6 AU (>7 AU)	Last obs. 9.4 AU. Mag. ~10 at 4.5 AU. Split at 4.9 AU.
Abell (1954 V) (1955–1956)	1954.23	4.496	82	> 7.4 AU	Last obs ~7.4 AU. Diffuse (5-7.3 AU).
Elias (1981 XV) (1981–1983?)	1981.63	4.743	142	> 5 AU	Narrow, parallel tail. Last obs. ~5-6 AU.
Sandage (1973 X) (1973–1975)	1973.85	4.812	536	> 4.8 AU	Last obs. ~6.5 AU diffuse.
Araya (1972 XII) (1972–1975?)	1972.97	4.861	476	> 4.9 AU	Obs. at 7 AU, mag. ~16.
Shoemaker (1988b) (1988–present)	1988.22	5.304	52		Coma at 9.5 AU.
Shoemaker† (1984 XV) (1984–1987)	1984.68	5.489	1624	> 7.8 AU	Coma at R = 10.3 AU.
Shoemaker (1986 XIV) (1987–present)	1986.89	5.457	38		Long tail at 9.6 AU.
West (1977 IX) (1976–1979)	1977.55	5.606	33	> 7.5 AU	Fan-shaped tail. Last obs. ~7.5 AU, tail.
Lovas (1976 XII) (1977–1978)	1976.83	5.715	142	> 6.8 AU	Last obs. ~6.8 AU with possible fanned tail.
Schwassmann-Wachmann 1 (continuous)	1989.70	5.772	SP		Exhibits ~ continuous activity 5 - 6.3 AU.

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Table 1. (continued)

Comet	T (years)	q (AU)	$(1/a)_{orig}$ (10^{-6} AU)	Tail	Comments
van den Bergh (1974XIII) (1974–1976)	1974.60	6.019	11	> 6.8 AU	Last obs. ~8.4 AU, diffuse.
Schuster (1975 II) (1976–1978)	1975.04	6.881	51	> 9.7 AU	Last obs. ~9.7 AU. Tail narrow and faint.
Chiron	1996.15	8.462	SP		Excess brightness at 17.5, 13 AU, coma at 11.8 AU.

†Class II comets (see text for explanation). § a = Tail dust grain size.

tails of distant comets exhibit a peculiar appearance. Sekanina (1973, 1975) has inferred that the tails are caused by the ejection of large (> 0.01 cm) particles at large distances and that this requires more volatile materials than water.

Based on the assumption that the sublimation activity for a comet nucleus depends on the most volatile species available, Delsemme (1985) deduced the heliocentric distances at which sublimation and coma formation began pre-perihelion for 7 new comets, 2 old comets in nearly parabolic orbits and 2 periodic comets by studying the light curves as a function of R. He fit vaporization curves to a homogeneous set of magnitude versus R data taken by Bobrovnikoff to determine r_o, the distance at which > 97.5% of the incident solar energy is used for reradiation. A similar technique has been used by Meech et al. (1986) to compare a homogeneous set of charge-coupled-device (CCD) observations of P/Halley from recovery (R = 11 AU) to inside R = 5 AU to deduce that activity began near R = 6 AU pre-perihelion, and that the formation of the coma was consistent with sublimation from a dark, slowly rotating H_2O-ice nucleus. This is the largest distance at which H_2O ice sublimation can be expected to contribute to sustained coma formation pre-perihelion. From both ground-based CCD observations/modelling and spacecraft observations, it is known that the activity in this comet *is* primarily controlled by H_2O-ice sublimation. At R = 6 AU, images of the comet appeared stellar, so it was the deviation in brightness from purely geometrical brightness variations (such as those exhibited by asteroids) that indicated the activity had begun, making this technique a very sensitive indicator of cometary activity. Delsemme's results show that, like the values for the short-period comets, the values of r_o are consistent with H_2O-ice sublimation for all of the nearly

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parabolic orbits. Unfortunately, the comets were not observed over a large range of R (most were observed out to 2 to 3 AU, and none were observed beyond $R = 4$ AU, in other words beyond the region where H_2O ice activity is expected to dominate). Furthermore, the distance at the onset of sublimation was nearly always determined by extrapolation from the data. In fact, Delsemme himself notes that none of the data cover a sufficient range in R to be completely conclusive. Additionally, the models assumed albedos between 0.1 and 0.7, which we know from the P/Halley encounter to be far too high. In short, Delsemme's claim that H_2O-ice sublimation controls the activity in *both* new and old comets was not conclusive.

Interestingly, Whipple (1978) analyzed a set of observations made by Beyer and Bobrovnikoff that included the same sample as the data used by Delsemme (1985), and concluded that the brightness variations as a function of R were *different* for the new and old classes of comets (precisely the opposite of the conclusion reached by Delsemme!). Unfortunately, the rate of brightening was measured using a power law fit to the light curves over whatever range of distances the observations were made. The shape of the light curve is a function of the range of R over which the observations are made—so this is not a valid comparison for comets observed over ranges of distances. Since no attempt was made to analyze the data over the same range of distances, it is impossible to interpret the results as showing a systematic difference in the behavior of new versus old comets.

One of the largest compilations of light curve data that presently exists is by Svoren (1983, 1984, 1985), who has summarized the photometric observations obtained from a wide variety of sources of nearly parabolic comets observed between 1861 and 1976. Although the data set has not been fully analyzed, Svoren discusses at length the problems inherent in combining data sets from many sources—including systematic brightness differences of up to 7.5 magnitudes, depending on observers, instrumentation, and method of observation! In his initial analysis of the photometric parameters of the light curves (Svoren, 1986), he finds no difference in light curve behavior versus R between dynamical classes.

3.3. SPECTROSCOPIC OBSERVATIONS

One of the original reasons for believing that sublimation processes in comets are controlled primarily by water ice (or water ice clathrate) is the fact that nearly all molecular emission lines appear almost simultaneously near $R \approx 3$ AU (Delsemme and Swings, 1952). Donn (1977) used the published spectra of 85 comets to make comparisons based on the number and type of molecular and ionic lines, dust-to-gas ratios and rates of change of brightness with distance. He concluded from his analysis that there is no evidence for a systematic difference between the new comets and the old ones. These conclusions were confirmed by A'Hearn et al. (1979), who looked at production rates, gas-to-dust ratios and colors of 4 periodic comets of widely varying perihelion distances. The properties exhibited by the comets in their sample were similar to those of new comets. On the other hand, Feldman et al. (1974) and Feldman and Brune (1976) made observations of the nearly parabolic comets Kohoutek (1973 XII) and West (1976 VI), respectively, and found unusually high abundances of CO or CO_2 implied. Comet Kohoutek was a dynamically new comet, whereas Comet West was not ($(1/a)_{orig} = 1569$; Marsden et al., 1978). The excess abundance of CO or CO_2 might be expected in the scenario in which new comets contain a larger fraction of more highly volatile species. The production rate of the volatile

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species for Kohoutek was inferred to be commensurate with that of water, whereas for Comet West, the source for CO was approximately 1/3 as abundant as water. This contrasts with the abundances of 3.5% CO_2 (Krankowsky et al., 1986) and 10% to 20% CO (Woods et al., 1986) found, from the recent encounter, for P/Halley. Another nearly parabolic comet that was not dynamically new, Comet Humason (1962 VIII; see Table 1), had a spectrum dominated by CO^+ at $R = 5$ AU (Dossin, 1966).

3.4. OUTBURSTS AND SPLITTING

Cometary brightness outbursts and nucleus splitting are often associated together, since splitting opens fresh surfaces to the Sun, increasing the surface area and activity. The cause of the splitting, however, is not well understood. Donn and Urey (1955) first suggested explosive chemical reactions as the cause. More recent spectroscopic observations suggest sublimation of more volatile ices (Hughes, 1975; Cochran et al., 1980; Feldman et al., 1986) or phase changes of amorphous to crystalline ices (Patashnick et al., 1974). In a survey by Hughes (1975) of cometary outburst characteristics, he finds no correlation of outbursts with R, outbound or inbound on the orbit, position in space, or dynamical age. From Sekanina's (1982a) review on cometary splitting, there likewise seems to be no distinction between old and new comets regarding nuclei breakup. Kresák (1977) compared a sample of roughly 50 old and 50 new comets on the basis of absolute brightness, change in brightness with distance from the Sun, light curve symmetry about perihelion, prevalence of continuous spectra and dust tails, and tendency toward splitting and outbursts, and found that none of these effects were statistically significant from one group to the other. He maintained that previous determinations of differences between groups may have been due to selection effects.

The results discussed above have been summarized in Table 2, which lists comparison criteria used to look for differences between new and old comets and whether or not systematic differences were detected. The comets used in the study are also indicated, along with references to the investigations. From the table, it is clear that in the literature there has been no past consensus regarding the question of conclusive observation differences, that may possibly be attributable to aging effects between orbital classes of comets. A large part of the problem has been the lack of a homogeneous set of data for systematic study. Comparing brightness observations over a wide range of heliocentric distances with models for the activity seems to be one of the most promising techniques for determining the cause of the activity. It is apparent that to accurately investigate cometary behavior over a wide range of distances to search for aging effects, individual comets need to be observed with a standard procedure throughout the maximum observable extent of their orbits. Unfortunately, in the past, data sets such as these have not existed. This has been in part because most comets are recovered and observed at distances between $R < 2$ and 3 AU, at which time activity has already begun and the comets are bright, and in part because of the long time spans required for the observations. With modern CCD detectors and large telescopes, however, it is now possible to accurately observe comets out to very large R. The next section deals with observations made in the past few years with modern detectors.

Table 2. Observational Evidence for Aging—Old Data

Comparison Criteria	Diff?	Comet	References
Orbital [*1/a* fading]	Yes	Many	Marsden et al. (1978)
[nongravitational]	No		Marsden et al. (1973)
			Weissman (1979)
Activity at Large *R*	Yes	Many	Various
			Sekanina (1975)
	No		Kresák (1977)
Light Curve Analysis	No	Many	Roemer (1962), Kresák (1977)
			Delsemme (1985), Svoren 1986
	Yes		Whipple (1978)
Intrinsic Brightness	Yes		Various
	No		Kresák (1977)
Spectral lines +	No	Many	Donn (1977), Kresák (1977)
Continuum		4 periodic	A'Hearn et al. (1979)
	Yes	Kohoutek, West	Feldman (1974, 1976)
Outbursts	No	Many	Hughes (1975), Kresák (1977)
Splitting	No		Kresák (1977), Sekanina (1982a)

4. Recent Evidence for Aging

At the end of the previous section, the need for systematic comprehensive studies was stressed. The past few years have seen the initiation of a few such programs. In addition, new detector technology has enabled observations of much fainter objects, which are greatly extending the distances to which comets can be observed. This section is divided into two parts, dealing with (i) large programs, and (ii) a comparison of individual observations.

4.1. Comprehensive Studies

4.1.1. *Spectroscopy.* Cochran et al. (1989a) have summarized the results of the ten-year McDonald Faint Comet Survey for which spectroscopic observations have been made for over 80 comets. The emphasis of this program is to study both individual properties of comets and group characteristics of a statistically significant sample. Cochran et al. have determined that comets fall into groups of low and normal activity with respect to gaseous emission band strengths (CN, C_3 and C_2). Cochran et al. (1989b) conclude that although the low-activity comets at first appeared to have systematically low production rate ratios for *log[Q(*C_2*)/log[Q(CN)]* and *log[Q(*C_3*)/log[Q(CN)]*, the upper limits to the ratios for the low-activity comets fall within the range of ratios for the normal comets. The comets studied by Cochran et al. (1989a) appear to be a fairly homogeneous group.

A similar analysis of gas and dust production rates as a function of R is being pursued by Newburn and Spinrad (1989). Their program to date has data for 25 comets. Combined, these types of studies should provide a good statistical basis of cometary behavior and activity, from which it should be possible to search for differences between dynamical classes of comets. These spectroscopic studies will be complementary to the photometric studies described below.

4.1.2. *Photometry*. Whereas the previous two studies are primarily involved in accumulating large statistical samples of cometary spectra over a range of distances, the author of this review has been undertaking a study of the photometric behavior of many comets, following each comet over a wide range of distances. In order to address the question of aging, CCD observations are being compared with simple sublimation models. The onset of cometary activity due to sublimation as a comet approaches the Sun will depend on the composition of the nuclear ices, which, as shown by Delsemme (1982), is a strong function of the heliocentric distance. In principle, for a nucleus composed of a single ice type, it should be possible to determine the composition based on the heliocentric distance at the onset of sublimation. The comparison involves the computation of the estimated brightness of the coma from scattered light from the dust within a fixed aperture. This technique has been successfully applied to Comet P/Halley for H_2O ice sublimation (Meech et al., 1986), and to observations of Comet Bowell (1982 I), a new comet. The Comet Bowell data could not be matched by H_2O ice sublimation; rather, a more volatile ice such as CO_2 (see Figure 5) was a much better representation of the data (Meech and Jewitt, 1987). The present data set consists of broadband CCD observations of ~50 comets made over a wide range of distances during the past five years. New comets are added to the list if (i) the orbit is likely to indicate that the comet is dynamically new, (ii) they are periodic comets that have aphelia much beyond 6 AU, or (iii) they are among those comets with especially large perihelion distances. The composition of the data set is intended to be a good representation of the various types of comets, based on dynamical class and orbital type. It is important to include comets of both large *and* small perihelion distances, q, since in the past, there has been an observational bias against comets of large q. The perihelion distance will play an important role in the amount and character of the mass loss during the passage through perihelion. Table 3 lists the well-observed comets currently in the program.

The thermal models used in the analysis of the data consider the energy balance at the nucleus surface. Comets tend to have very individual behaviors, even within the same dynamical classes; therefore, without detailed information on such things as the internal structure in the nucleus, grain size distribution, dust-to-gas ratios, surface structures, and nucleus rotational state, it is impossible to construct a detailed model that will uniquely represent the nucleus to the extent that the composition may be deduced. (The only comet nucleus for which a very large body of data exists that would begin to permit this type of modelling is that of P/Halley.) However, the discovery of basic information related to the

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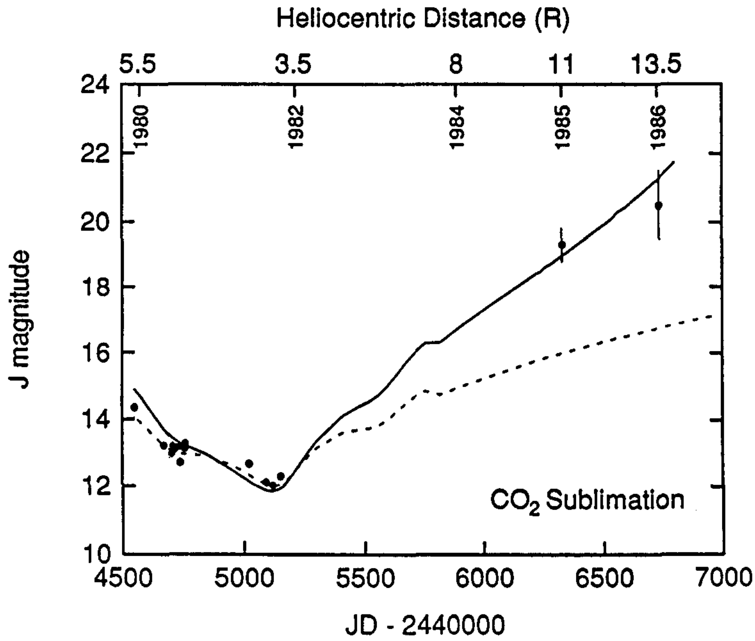

Figure 5. J magnitudes within a 5-arcsec radius diaphragm are plotted versus JD for Comet Bowell. The heliocentric distances and dates are marked at the top of the graph. A CO_2 sublimation model is shown as a solid line, and the dashed curve represents the brightness variation that Comet Bowell would have if the intrinsic coma brightness remained unchanged. H_2O models do not fit the data; they fit as poorly as the constant coma model does, for all reasonable ranges of input parameters. This figure is after Figure 4 from Meech and Jewitt (1987).

amounts of ices present that are more volatile than H_2O (i.e., gross behavioral differences, possibly attributed to evolutionary effects) is possible with this technique.

Nearly 10 comets in the program now have sufficient heliocentric distance coverage (observations at six or more distances, ranging from < 1 AU to beyond 15 AU) to begin comparison with H_2O (and more volatile) ice models. The preliminary results are beginning to suggest that there *are* differences between the periodic and Oort comets. Some comets, such as comets Bowell and Cernis, which at R = 13.5 and 14.1, respectively, were *still* diffuse, indicate that some process other than H_2O ice sublimation is controlling the activity. Figure 6 shows an image of Comet Cernis (1983 XII) at R = 15.3 AU (April, 1989). Whereas there was an extended coma on Cernis at least 2×10^5 km in diameter at 14.1 AU, field crowding at R = 15.3 AU makes determining the extent of the coma extremely difficult. The fact that it is still visible at this distance (magnitude ~20) suggests either that it has an extremely large nucleus (radius ~15 times that

Table 3. Well-Observed Comets in the Current Program

Comet	q (AU)[1]	Q (AU)[2]	Range in R[3]	# R[4]	Obs_q[5]	Obs_Q[6]	Recover[7]
Arend-Rigaux	1.45	5.76	1.5 - 5.7	10		x	
Austin	0.35	—	0.7	New			
Borrelly	1.36	5.86	1.4 - 2.1	4			
Bowell	3.38	—	3.5 - {20.1}	{7}			
Brooks 2	1.85	5.40	1.8 - 1.9	3			
Cernis	3.33	—	3.3 - 17.4	6	x		
Chiron	8.46	18.82	11.1 - 14.2	13			
Churyumov-Solodovnikov	2.64	—	5.6 - {12.0}	5			
Comas Sola	1.83	6.68	3.0	1			
d'Arrest	1.29	5.59	2.3 - 4.9	9			x
Encke	0.33	4.09	0.9 - 4.1	9		x	
Giacobini-Zinner	1.03	6.00	1.0 - 5.8	6		x	
Grigg-Skjellerup	0.99	4.93	1.2 - 4.9	4		x	
Gunn	2.47	4.74	2.5 - 4.6	4			
Halley	0.59	35.29	0.8 - 12.9	22	x		
Hartley 1985XIV	4.00	—	6.2 - {11.2}	5			
Holmes	2.17	5.21	2.7 - 3.3	2			
Jensen-Shoemaker	3.33	—	4.6 - {7.7}	3			
Klemola	1.77	8.09	1.9 - 4.5	6			
Kohoutek	1.78	5.30	2.5	1			
Kopff	1.58	5.35	2.3 - 4.7	8			x
Machholz	0.12	5.91	4.8 - 5.8	3			
Neujmin 1	1.55	12.29	3.9 - 10.7	14			
Schwassmann-Wachmann 1	5.77	6.31	5.8 - 6.0	12			
Schwassmann-Wachmann 2	2.07	4.81	2.8 - 4.3	3			
Shoemaker 1985XII	2.70	—	4.9 - 12.7	14			
Shoemaker 1986XIV	5.46	—	5.8 - 9.6	11			
Shoemaker '88b	5.30	—	5.7 - 9.5	7			
Smirnova Chernykh	3.56	4.77	4.5 - 4.7	4		x	
Tempel 2	1.38	4.69	1.4 - 4.2	14	x		
Torres	3.62	—	3.6 - 8.8	9	x		
Wild 2	1.58	5.29	4.0 - 5.3	5		x	
Wilson	1.20	—	1.2 - 7.8	12	x		

{ } Indicates brightness limit
[1] Perihelion distance in AU
[2] Aphelion distance
[3] Range of heliocentric distances for observations
[4] Number of distances at which observations exist
[5] Perihelion observation
[6] Aphelion observation
[7] Recovery observation

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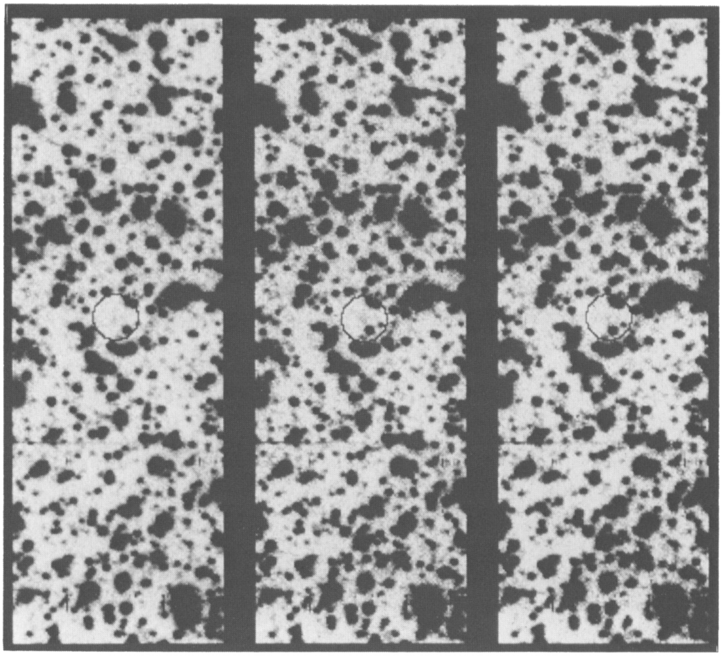

Figure 6. Three R-band CCD images of Comet Cernis obtained with the 1.5-m telescope at the Cerro Tololo Interamerican Observatory (CTIO) on April 6, 1989. The comet was at $R = 15.33$ AU and had a total integrated magnitude, within a 5-arcsec aperture, of ~20. Cernis is centered within the circle in each image, which correspond to 4:25, 4:41 and 4:50 UT, respectively, moving from left to right. Each image is 1 by 3 arcmin in size. North is at the bottom and east to the left in these frames.

of P/Halley) or that it still has an extensive coma. If a coma exists, then it is comparable to the extensive comae typically found in other program comets on nearly parabolic orbits. Comet Shoemaker (1986 XIV) has maintained an extensive, narrow tail throughout its ~3 years of observation. At $R = 7.65$ AU, the tail was greater than 1.2×10^6 km in length (Figure 7). The appearance is very similar to the typical narrow tail morphology reported by Sekanina (1975) for icy tails at large R. For comparison, periodic comets such as P/Tempel 2 do not show activity until very close to the Sun (between $R \approx 2.2$ and 2.4 AU), indicative of a surface layer of insulating dust that inhibits sublimation. Comet P/Kopff likewise did not begin to develop a coma until relatively close to the Sun, near $R \approx 3.4$ AU. The periodic light curves are characterized by "asteroidal" brightness variations (lack of activity, or purely geometric brightness changes due to changing distance) until near perihelion ($R \approx 6$ AU for P/Halley, $R < 4$ AU for P/Neujmin 1, $R \approx 3.4$ AU for P/Kopff and $R \approx 2.2$ AU for P/Tempel 2). The dynamically new comets, on the other hand, are characterized by visible comae over a wide range of distances.

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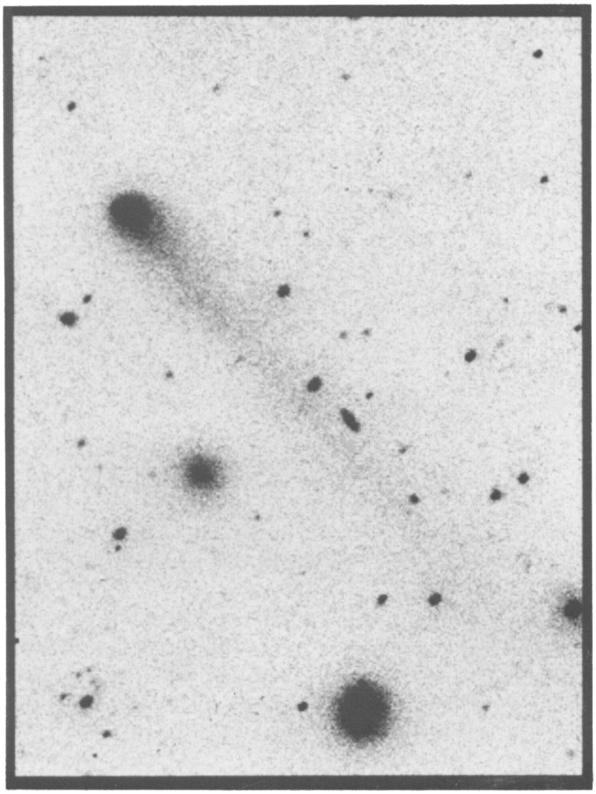

Figure 7. 500-s R-band CCD image of Comet Shoemaker 1986 XIV obtained using the University of Hawaii (UH) 2.2-m telescope on December 9, 1988. The comet was at a heliocentric distance of $R = 7.65$ AU and a geocentric distance, $\Delta = 7.97$ AU. The tail extends off the CCD. The field shown is 3 by 4 arcmin, which implies a projected tail length $> 1.2 \times 10^6$ km. North is to the left and east to the bottom in this image.

Figure 8 compares the photometric data for all of the well-observed comets in the program. All of the periodic comets are plotted as (+), and the dynamically new comets are plotted as (x). Because P/Halley is atypical of the short-period comets in the sense that it is unusually active, it has been plotted with filled circles pre-perihelion and open circles post-perihelion. Data for Chiron are plotted as boxes and will be discussed in Section 4.2.5. The periodic comet data contain both pre- and post-perihelion observations, and with the exception of the observations of P/Halley, all points are significantly fainter than for the new comets. Due to obvious selection effects (new comets are discovered fairly close to the Sun), most of the new comet data represent post-perihelion observations. Nevertheless, it appears that the new comets are generally brighter than the periodic comets at similar heliocentric distances. Although the post-perihelion light curve of P/Halley is very similar to those of the new comets, near 10 AU, the post-perihelion brightness begins

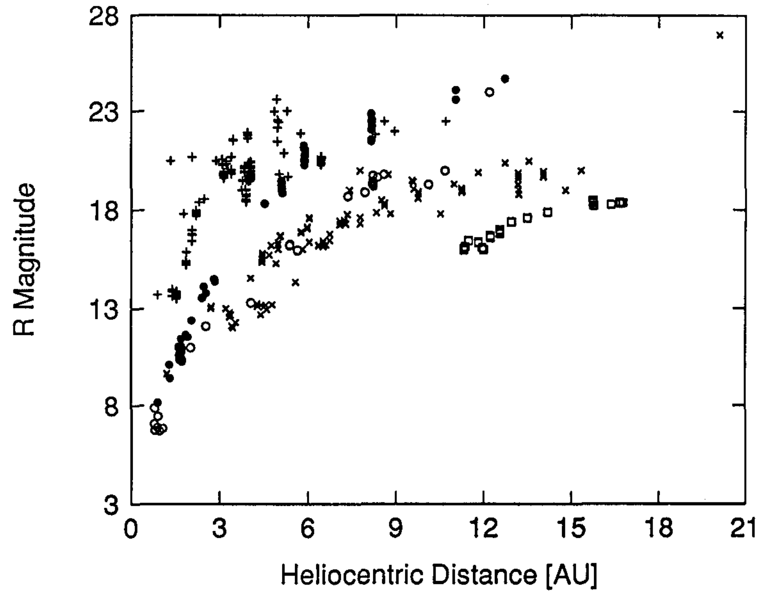

Figure 8. R magnitudes within a 5-arcsec radius aperture versus heliocentric distance for the well-observed comets in the present program. Pre-perihelion P/Halley measurements are plotted with filled circles, and the post-perihelion data are plotted with open circles. All other periodic comets are plotted with (+). The dynamically new comets are plotted with (x) and the object Chiron with boxes.

to return to its pre-perihelion value, indicating the cessation of activity. In contrast, the new comets do not yet show this trend, with the possible exception of Comet Bowell. The data point at $R = 20$ AU, magnitude ~27 represents a possible detection of Bowell during December 1989 with the 3.8-m Canada-France-Hawaii Telescope (CFHT) in Hawaii. Pending further observations, this will be either a brightness upper limit or a detection, either of which indicates that there has been an abrupt change in brightness, most likely due to a cessation of activity and the disappearance of a coma somewhere between 14 and 20 AU.

It could be argued that this sort of compositional analysis would best be studied spectroscopically when the comet is near perihelion. Instead of an "indirect" determination of the composition based on the distance at which the production of a dust coma begins, spectroscopic observations could determine molecular gas species directly. The problem, however, lies not only in determining which species are the "parents" and which are the daughters, but also in the present impossibility of studying the comets at such large distances spectroscopically because of the extreme faintness and low-surface-brightness comae (25 to 27 magnitudes arcsec^{-2}). Cochran (1987) has shown that there is no trend with R in the ratio of $log[Q(C_2)/log[Q(CN)]$ and $log[Q(C_3)/log[Q(CN)]$ in the McDonald Observatory data. This would suggest that the most direct way to determine the

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composition would be to obtain spectra of the comets near perihelion, when they are bright. Unfortunately, as pointed out by Cochran et al. (1989a), very few comets exhibit emission bands for species other than CN beyond $R > 2.5$ AU; however, many comets of interest in this program have perihelion distances greater than this. Furthermore, the McDonald data included observations out to only $R = 4.8$ AU (P/Halley), and the set included virtually no Oort comets (only two are listed in Cochran et al., 1989a, and Cochran, 1987). Given that H_2O-ice dominated activity begins near 6 AU, and given that differences in activity may often best be determined at $R > 6$ AU where typically *only* species more volatile than H_2O will be active, it appears that a spectroscopic study of comets at *large R* is necessary to search for differences. Many of the comets described above, and others in the author's present program, are simply too faint for this method to be practical (magnitudes 20 to 24). In addition, there are virtually no data on variation in molecular emissions as a function of R for the few comets that have been observed spectroscopically at large R. Comet Humason (1962 VIII) had a highly unusual spectrum at $R = 5$ AU, with CO^+ much stronger than CN (Dossin, 1966). In fact, the spectrum of the comet was similar at perihelion ($q = 2.133$ AU; Greenstein, 1962). Because there is no homogeneous set of spectroscopic observations as a function of R (out to large R) for comparison against, the most logical way to search for differences between comet activity at large and small R is to model and compare the *brightness*, extended over a range of distances.

4.2. INDIVIDUAL RESULTS

4.2.1. *Activity at Large R.* The trend in the photometric data described above indicated that dynamically new comets exhibit excess activity at very large R. The short-period comets do not exhibit such activity out to large distances. The one exception has been Comet P/Halley. Both the present observations and those made by West and Jørgensen (1989) and West (1989) show that the coma of P/Halley continues to persist even out to beyond 10 AU. Figure 9 shows the coma of P/Halley detected with the Kitt Peak 4-m telescope when the comet was at $R = 10.70$ AU (April 1989). The extent of the visible coma is $> 1.4 \times 10^5$ km. West and Jørgensen (1989) show that the coma in April and May 1988 had two distinct regions and that the inner coma was substantially fainter in May, suggestive of a sharp decline in activity. Between May 1988 ($R = 8.5$ AU) and January 1989 ($R = 10.1$ AU), the dust density in the coma remained unchanged, suggesting that activity had ceased sometime beyond $R = 8.5$ AU. This is in contrast to observations for many of the new comets, whose brightnesses do not decrease as rapidly as would be expected from geometry alone for inactive bodies. The new comets are probably active at large distances (see, for example, Comet Bowell: Meech and Jewitt, 1987; Houpis and Mendis, 1981). On the other hand, Sekanina (1982b) has hypothesized that the coma of Comet Bowell was a remnant of the comet's formation and not a product of active sublimation, so the assertion that these comets exhibit activity is still controversial. Although the sample at such large distances is very limited, and P/Halley appears to be an unusual short-period comet, a possible basic difference between the new and old comets is becoming evident.

4.2.2. *Perihelion Brightness Asymmetry.* Although a large database is being created for observations versus R, the majority of the observations are made post-perihelion. Many comets exhibit pronounced brightness asymmetries about perihelion. Post-perihelion

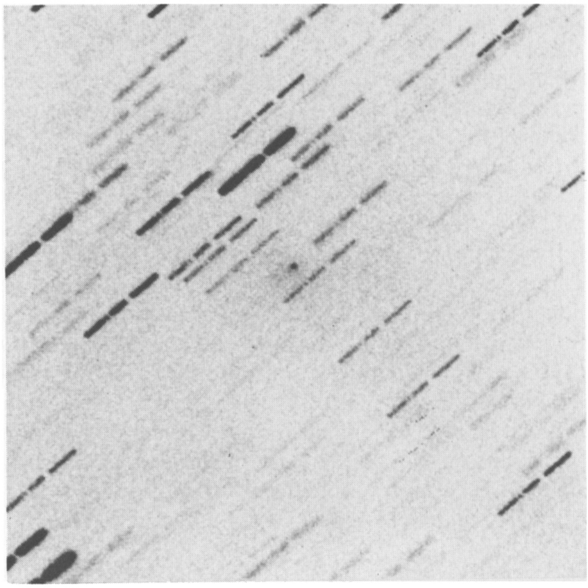

Figure 9. CCD R-band images of P/Halley obtained by K. Meech and M. Belton using the Kitt Peak 4-m telescope on April 9, 1989. The comet was at R = 10.70 AU and Δ = 10.11 AU. The field of view of the image is 3 by 3 arcmin, with the visible projected coma extending at least 1.4×10^5 km in the plane of the sky. North is to the top and east to the left in this image.

brightness excesses are probably due to a thermal lag or penetration of heat into the interior of the nucleus post-perihelion (Smoluchowski, 1986) or possible seasonal effects (Weissman, 1987). The coma of P/Halley did not develop pre-perihelion until R = 6 AU, whereas it maintained an extensive coma post-perihelion—out beyond R = 10 AU. The large post-perihelion brightness excess for P/Halley is illustrated nicely in Figure 10a (Green, 1989), which is a light curve of CCD dust and visual observations. The same trend is seen in the gas production rate light curve in Figure 10b (reproduced from Divine and Newburn, 1987). In contrast, for Comet Wilson, a dynamically new comet, the opposite trend is apparent. From International Ultraviolet Explorer (IUE) observations of the evolution of comets Wilson and P/Halley, Roettger et al. (1989) found that near R = 1.2 AU pre-perihelion, the water production rates for the two comets were similar, whereas farther out pre-perihelion, Wilson had a higher water production rate. Post-perihelion, the P/Halley water production rates were much higher than those for Wilson. Likewise, the continuum flux (dust) was higher in Wilson pre-perihelion than in P/Halley and then followed the same trend as the gas production post-perihelion. These authors attribute the different behavior in Comet Wilson to the possible loss of a highly volatile layer from the surface of the comet. The results are summarized in Figure 11 (after Roettger et al., 1989). Supporting this interpretation are observations by Arpigny et al. (1988) which show that the CO_2^+/OH^+ band strength ratio was much higher in Wilson

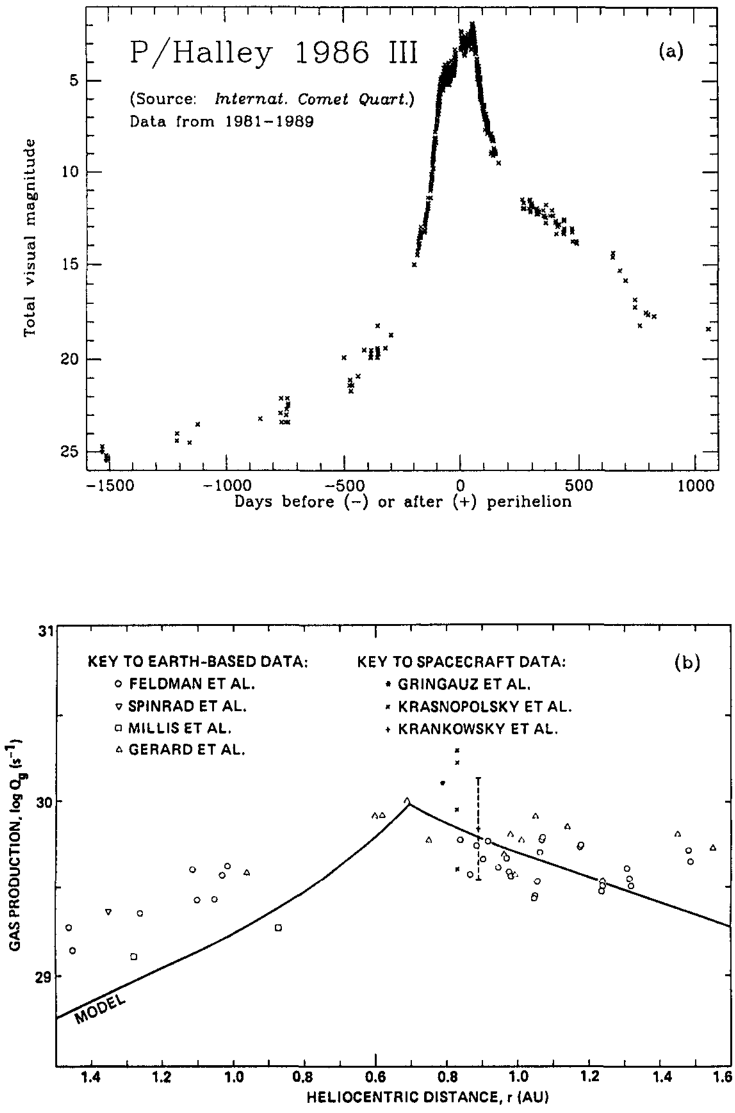

Figure 10. (a) Light curve of P/Halley showing post-perihelion brightening (Green, 1989), which is an update of the International Comet Quarterly (ICQ) archive light curve shown in Green and Morris (1987). (b) The same trend is seen in the gas production rates in this figure reproduced with permission from Divine and Newburn (1987), Springer-Verlag.

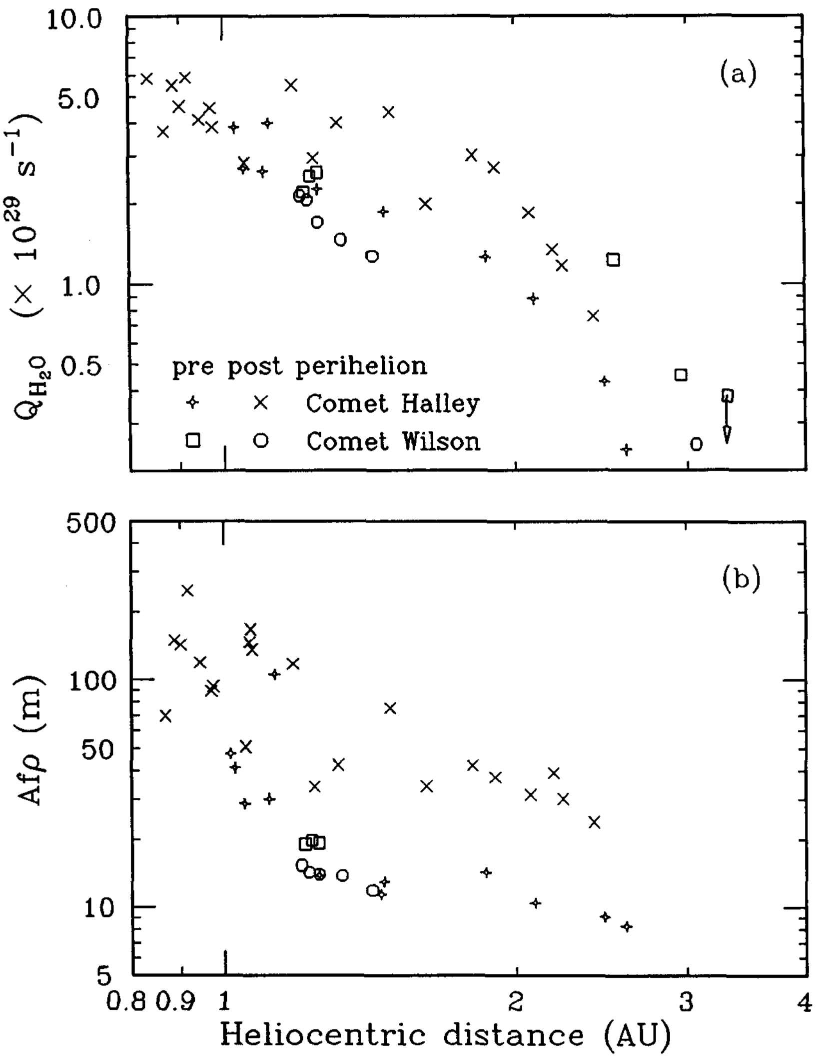

Figure 11. (a) Water production rates from IUE observations of OH emissions versus heliocentric distance for comets P/Halley and Wilson. Both curves show asymmetries about perihelion; however, the two comets behave in an opposite manner. (b) The quantity Afρ, which is a measure of the dust production, is plotted versus distance. The same trends are seen in the gas and dust. This is Figure 3 reproduced with permission from Roettger et al. (1989), Academic Press.

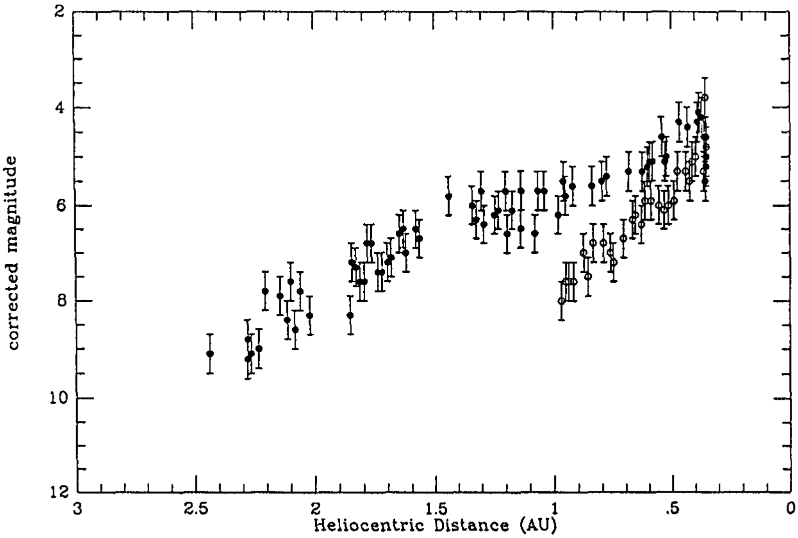

Figure 12. Visual observations compiled by D. Tholen, from data taken published in the IAU Circulars, of the dynamically new Comet Austin as a function of heliocentric distance. The observations have been corrected to unit geocentric distance by subtracting 5.0 log (Δ). The pre-perihelion observations are plotted as filled circles, and the post-perihelion data as open circles.

than in P/Halley. Both Arpigny et al. (1988) and Cremonese and Fulle (1989) noted the fading or mass loss decrease as Wilson approached perihelion.

The recently discovered Comet Austin (1989c$_1$; Austin, 1990), also a dynamically new comet (Marsden, 1990a, 1990b), has been observed from R = 2.44 AU, pre-perihelion, to the present, near R = 1 AU (May 1990), and has shown a steady decrease in brightness since perihelion on April 9.97, 1990, at q = 0.350 AU. Figure 12, compiled by D. Tholen, shows the visual light curve of Comet Austin corrected to unit geocentric distance, using observations reported in the International Astronomical Union (IAU) Circulars. The asymmetry is clearly apparent in the figure. Pre-perihelion IUE observations by Roettger and Feldman (1990) showed that the H_2O production rate in Austin was roughly twice that of Halley pre-perihelion at the same heliocentric distance, R = 2.2 AU. Comet Austin is similar to Comet Wilson in this respect. Sekanina (1990) has also inferred, from observations of the dust tail of Austin in February and March of 1990, that the tail is comprised of submillimeter grains ejected from the nucleus somewhere between R = 10 and 7 AU pre-perihelion. This is characteristic of other Oort cloud comets and may suggest the presence of more volatile species controlling the activity at large R. Interestingly, spectra taken in mid-March 1990, at R = 0.77 AU (Schleicher et al., 1990), show that the relative production rates of CN, C_2, and C_3 appear to be "normal," that is, typical of the comets observed by Cochran et al. (1989a). It is possible that the production rates of these species are not correlated with the volatiles possibly

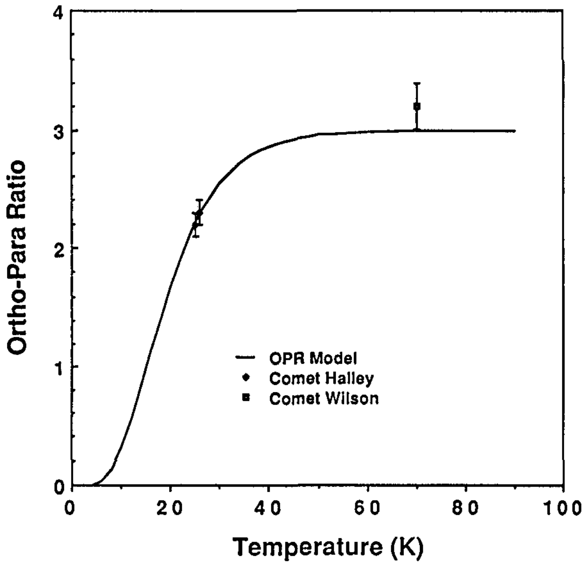

Figure 13. The observed values of the ortho-para ratios for comets P/Halley and Wilson are plotted versus the nuclear spin temperature. The solid line is the model for the OPR in thermal equilibrium. The figure shows a higher OPR for Wilson, suggesting that the measurements were made of a radiation-damaged surface layer on this new comet. See text for discussion. This is Figure 4, reprinted with permission from Mumma, M. (1989), Pergamon Press.

responsible for activity at large R. At present, there is insufficient data to answer this question.

4.2.3. *Infrared Spectroscopy.* The use of infrared (IR) spectroscopy to obtain the ortho-para spin ratio (OPR) and hence the nuclear ice spin temperature has already been discussed in the first section. The comparison of the results for the two comets thus far observed, P/Halley and Wilson, is particularly interesting. These are shown in Figure 13 (Mumma, 1989). The OPR for P/Halley was between 2.2 and 2.3 ± 0.1, consistent with a nuclear spin temperature of ~25 K, yet the OPR for Wilson was 3.2 ± 0.2, which is consistent with statistical equilibrium (OPR = 3.0) and much higher temperatures. Mumma et al. (1989) interpret this result as reflecting the fact that the measurements for P/Halley referred to the relatively pristine interior of the comet, whereas the Wilson measurement was for the outer layer of a new comet that had been modified by cosmic ray processing. This is one of the most direct pieces of evidence for a difference between an old comet and a dynamically new one.

4.2.4. *Outbursts and Variability.* The belief that the outgassing from cometary nuclei was approximately isotropic was completely overturned with the P/Halley spacecraft encounters. Giotto observations showed that only ~10% of the total surface area of P/Halley was involved in active sublimation and that the activity was restricted primarily to jets (Keller et al., 1987). This may provide an explanation for the fact that IUE observations of the water production rates in Comet P/Halley show rapid variability near perihelion (Feldman et al., 1987). Activity has even been reported at large distances both pre-perihelion (Festou et al., 1986) and post-perihelion (West and Jørgensen, 1989). The observations of Comet Wilson showed no such variation in the UV (Roettger et al., 1989) or in the near and thermal IR (Hanner and Newburn, 1989). Wilson was observed to have split post-perihelion (Meech, 1988a), somewhere near $R = 2$ AU, according to Sekanina (1988). In contrast to the UV and visible observations, Very Large Array (VLA) radio observations of OH emission showed that the emissions varied smoothly as a function of distance for P/Halley, while they were very erratic for Comet Wilson (Palmer et al. 1989). Both comets were at nearly the same distance pre-perihelion when the observations were made. Furthermore, the OH emission for P/Halley was confined to a region within $\sim 10^5$ km of the nucleus, but in the case of Wilson, sporadic blobs of variable intensity and velocity were measured up to 10^6 km away. At such large distances, the density was so low that Palmer et al. (1989) postulated that another source of OH was needed. They suggested that this might be evidence for fragments of crust, or Whipple's "volatile frosting," blown off Comet Wilson.

4.2.5. *Chiron.* Object 2060 Chiron, classified as an asteroid, has generated tremendous interest recently because as it approaches its 1996 perihelion, it has been systematically brightening more rapidly than the expected asteroidal brightness law, or geometrical considerations alone. The brightening was first reported in February 1988 (Tholen et al., 1988). At the time the brightening first began, this object was 13.0 AU from the Sun. Chiron has a very unusual orbit in the outer Solar System, with an aphelion of 18.8 AU, a perihelion of 8.5 AU and a period of about 50.4 years. Because the brightening has been systematic since mid 1987, Hartmann et al. (1989) believed that the observations strongly suggested that sublimation of volatile materials was the cause for the increase. Confirmation of cometary activity was obtained when a faint coma was detected (Meech and Belton, 1989). An example of this coma is shown in Figure 14, obtained on December 27, 1989, with the CFH telescope when Chiron was at $R = 11.32$ AU. Sublimation models show that water ice cannot be responsible for the activity, even though Chiron has a large surface area (diameter ~180 km); however, the brightening *can* be caused by scattering from a dust coma that is being produced from sublimation of a more volatile ice. Meech and Belton (1990) have shown that the coma is actually composed of submillimeter dust particles that have escaped from a gravitationally bound dust atmosphere. The coma and atmosphere may have been populated by episodic activity from two regions only 1 to 2 km in extent. The orbit of Chiron is chaotic (unstable on time scales of a few thousand years), and there is dynamical evidence that Chiron is evolving inward from the outer Solar System into an orbit similar to those of the short-period comets (Scholl, 1979; Oikawa and Everhart, 1979). Chiron thus may be an example of a new comet evolving inward that has not yet lost all of its more volatile species. Theoretical calculations by Stern (1989b) confirm the idea that Chiron may have spent most of its time beyond $R = 20$ AU.

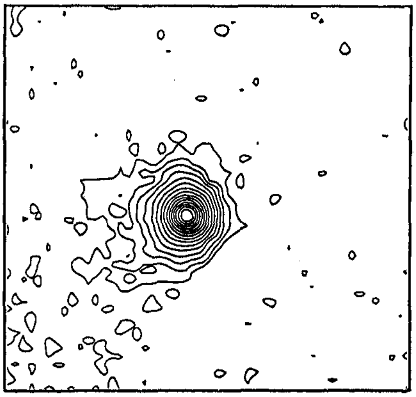

Figure 14. Contour plot from R-band CCD images of Chiron and coma taken by the author on December 27, 1989, with the CFH 3.8-m telescope on Mauna Kea. At the time, Chiron was $R = 11.32$ AU and $\Delta = 10.35$ AU away from the Sun and Earth, respectively. The plot is 30 arcsec on a side, and the coma extends ~10 arcsec from the nucleus in the antisolar direction (PA ~316 degrees). North is to the bottom and east is to the right in this image. The lowest plotted contours are at 24.8 magnitudes/arcsec^2, and each contour increases by 0.5 magnitude.

5. Looking to the Future

The conclusions regarding differences between comet classes from recent data are summarized in Table 4. Although the recent data set is still based primarily on a very small number of comets, many of these have been extensively observed. While it is true that comets are very individual objects, and that without a statistically significant sample it is difficult to draw conclusions about comet classes, the consensus among recent observers is that the evidence strongly suggests that the dynamically new comets are very different from the periodic comets. The new comets exhibit much greater activity at large R. In the case of Comet Wilson, at least, there was spectroscopic evidence for enhanced CO_2^+. There is not yet enough evidence to indicate whether these differences are due to aging or to different source regions. One piece of evidence favoring the aging hypotheses is the fact that among the group of nearly parabolic comets alone, there is evidence of a difference between the dynamically new comets ($(1/a)_{orig} < 100$) and the old ones (see Figure 4). On the other hand, the old comets in nearly parabolic orbits are typically brighter than the periodic comets. This can be interpreted either as an aging process (the periodic comets have spent considerable time within the near-Solar vicinity), or as a primordial difference in formation conditions. At present, it is not possible to distinguish between these two possibilities. More systematic data will need to be obtained on a large number of comets over a range of distances before this question is resolved.

One of the primary difficulties in obtaining observations over a large range of distances both pre- and post-perihelion is in recovering the comets at large distances, well before perihelion and the onset of sublimation. Unfortunately, recoveries, like most observations of short-period comets, are typically between the distances $R = 2$ to 3 AU,

Table 4. Evidence for Aging—Recent Observations

Criteria	Diff?	Comet Examples: New	Comet Examples: Periodic	References
Activity at Large R	Yes	Typical, pre- & post-perihelion Cernis & others Bowell	Unusual, only P/Halley	West and Jørgensen (1989) West (1989) Meech (1988b) Meech and Jewitt (1987)
Modelling/ Volatiles	Yes	Bowell—CO_2 Chiron(?)—CO	Halley—H_2O	Meech et al. (1986) Meech and Jewitt (1987) Meech and Belton (1990)
Intrinsic Brightness	Yes	Typically brighter		Present work
Brightness Asymmetry	Yes	Wilson—faded Austin—faded Kohoutek—faded	Halley—brighter	Roettger et al. (1989) Arpigny et al. (1988) Green and Morris (1987)
Production Rates	Yes	Wilson, Austin high w.r.t. Halley pre-perihelion		Roettger et al. (1989) Roettger and Feldman, 1990
Spectral Lines	No?	CN, C_2, C_3 same for Oort and old		Cochran et al. (1989)
	Yes	CO_2^+ enhance—Wilson Ortho-Para ratio		Arpigny et al. (1988) Mumma et al. (1989)
Colors	No	V-R=0.43±0.03 (5 comets)	V-R=0.42±0.10 (5 comets)	Meech, unpublished Jewitt and Meech (1988a)
		J-H=0.42±0.05 (9 comets)	J-H=0.45±0.07 (26 comets)	Hanner and Newburn (1989) Jewitt and Meech (1986) Jewitt and Meech (1988) Tokunaga et al. (1988)
Coma Size	Yes	> 10^5 km at 8 AU (4 comets)	10^4 km 1.5 to 3.5 AU (9 comets)	Meech (1988b) present work
		> 10^4 km (4 AU) (8 comets)	> 3×10^5 km (~8.6 AU) (Halley post-perihelion)	

at which time activity may have already begun on the nucleus. Recent recoveries, since 1980, clearly show that most comets are recovered near perihelion, between 1.5 and 3.5 AU. Out of the ~80 comets recovered since 1980, only Comet P/Halley was recovered beyond the region where H_2O ice sublimation is important in creating a coma. Thus, with the exception of P/Halley and several heavily mantled old comets, such as P/Tempel 2, there has been little opportunity to study the development of a periodic comet from its inactive state through perihelion. Until early recoveries at large R are made beyond 6 AU, it will be very difficult to use the light curve analysis alone to distinguish sublimation activity as being caused by different ices. It is therefore very important to make comet recoveries at large R to search for activity from very volatile species, such as have been seen in dynamically new comets. Unfortunately, very few of the dynamically new comets are discovered at large R pre-perihelion. Comet Bowell, one of the exceptions, was discovered with a coma pre-perihelion at $R = 7.3$ AU (Bowell, 1980). Lack of large-R observations pre-perihelion of the new comets will hinder the understanding of perihelion brightness asymmetries; however, comparisons may still be made of the post-perihelion behavior of the two groups.

It is clear that in order to answer these questions, a statistical sample of observations must be made over as wide a range of heliocentric distances as possible. New detector technology, combined with large telescopes and fast computers, will provide the instrumentation required to reach these goals.

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References

A'Hearn, M.F., and P.D. Feldman (1984). "S_2: A Clue to the Origin of Cometary Ice?", in Ices in the Solar System, eds. J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski, NATO Adv. Sci. Inst. Series C, Vol. 156, D. Reidel Pub. Co., Dordrecht, pp. 463–471.

A'Hearn, M.F., P.D. Feldman, and D.G. Schleicher (1983). "The Discovery of S_2 in Comet IRAS-Araki-Alcock," Astrophys. J. Lett. 274, L99–L103.

A'Hearn, M.F., R.L. Millis, and P.V. Birch (1979). "Gas and Dust in Some Recent Periodic Comets," Astron. J. 84, 570–579.

Arpigny, C., F. Dossin, J. Manfroid, P. Magain, and R. Haefner (1988). "Pre- and Post Perihelion Spectrographic and Photometric Observations of Comet Wilson (1986l)," Messenger 51, 27–31.

Austin, R.D. (1989). "Comet Austin (1989c$_1$)," IAU Circ. No. 4919.

Bailey, M.E. (1985). "The Problem of the 1/a-Distribution and Cometary Fading," in Dynamics of Comets: Their Origin and Evolution, IAU Colloquium No. 83, eds. A. Carusi, and G.B. Valsecchi, D. Reidel Pub. Co., Dordrecht, pp. 311–317.

Bar-Nun, A., and D. Prialnik (1989). "Formation of Comets—Laboratory Studies and Modelling," in Asteroids, Comets, Meteors III, Abstracts, Uppsala Astronomical Observatory Report No. 48, Uppsala, #11.

Barnard, E.E. (1890). "Comets 1889 I and II, and Some Suggestions as to the Possibility of Seeing the Short-Period Comets at Aphelion," Astron. J. 10, 67–68.

Belton, M.J.S. (1965). "Some Characteristics of Type II Comet Tails and the Problem of the Distant Comets," Astron. J. 70, 451–465.

Bowell, E. (1980). "Comet Bowell (1980b)," IAU Circ. No. 3465.

Brin, G.D., and D.A. Mendis (1979). "Dust Release and Mantle Development in Comets," Astrophys. J. 229, 402–408.

Cochran, A.L. (1987). "Another Look at Abundance Correlations Among Comets," Astron. J. 93, 231–238.

Cochran, A.L., E.S. Barker, and W.D. Cochran (1980). "Spectrophotometric Observations of P/Schwassmann-Wachmann 1 During Outburst," Astron. J. 85, 474–477.

Cochran, A.L., J.R. Green, and E.S. Barker (1989a). "Are Low Activity Comets Intrinsically Different From More Active Comets?", Icarus 79, 125–144.

Cochran, A.L., J.R. Green, and E.S. Barker (1989b). Erratum. Icarus 80, 446.

Cremonese, G., and M. Fulle (1989). "Photometric Analysis of the Dust Tail of Comet Wilson 1987VII," poster paper presented at the "Comets in the Post-Halley Era" meeting, Bamberg, FRG.

d'Hendecourt, L.B, L.J. Allamandola, R.J.A. Grim, and J.M. Greenberg (1986). "Time-Dependent Chemistry in Dense Molecular Clouds. II. Ultraviolet Photoprocessing and Infrared Spectroscopy of Grain Mantles," Astron. Astrophys. 158, 119–134.

Degewij, J., and E.F. Tedesco (1982). "Do Comets Evolve into Asteroids? Evidence From Physical Studies," in Comets, ed. L.L. Wilkening, University of Arizona Press, Tucson, Arizona, pp. 665–695.

Delsemme, A.H. (1975). "Physical Interpretation of the Brightness Variation of Comet Kohoutek," in Comet Kohoutek, ed. G.A. Gary, Scientific and Technical Information Office, NASA, Washington, pp. 195–203.

Delsemme, A.H. (1982). "Chemical Composition of Cometary Nuclei," in Comets, ed. L.L. Wilkening, University of Arizona Press, Tucson, Arizona, pp. 85–130.

Delsemme, A.H. (1985). "The Sublimation Temperature of the Cometary Nucleus: Observational Evidence for H_2O Snows," in Ices in the Solar System, eds. J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski, NATO Adv. Sci. Inst. Series C, Vol. 156, D. Reidel Pub. Co., Dordrecht, pp. 367–387.

Delsemme, A.H., and P. Swings (1952). "Hydrates de Gaz Dans les Noyaux Comètaires et les Grains Interstellaires," Ann. d' Astrophys. 15, 1–6.

Divine, N., and R.L. Newburn (1987). "Modelling Halley Before and After the Encounters," Astron. Astrophys. 187, 867–872.

Donn, B. (1976). "The Nucleus: Panel Discussion," in The Study of Comets, ed. B. Donn, M. Mumma, W. Jackson, M. A'Hearn, and R. Harrington, NASA SP-393, Part 2, Washington, D.C., pp. 611–621.

Donn, B. (1977). "A Comparison of the Composition of New and Evolved Comets," in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, ed. A.H. Delsemme, University of Toledo, Toledo, Ohio, pp. 15–23.

Donn, B., and H.C. Urey (1955). "On the Mechanism of Comet Outbursts and the Chemical Composition of Comets," Astrophys. J. 123, 339–342.

Dossin, F.V. (1966). "Emission Spectrum of a Comet, at Large Heliocentric Distance," Astron. J. 71, 853–854.

Duncan, M., T. Quinn, and S. Tremaine (1988). "The Origin of Short-Period Comets," Astrophys. J. 328, L69–L73.

Everhart, E., and B.G. Marsden (1983). "New Original and Future Cometary Orbits," Astron. J. 88, 135–137.

Everhart, E., and B.G. Marsden (1987). "Original and Future Cometary Orbits. III," Astron. J. 93, 753–754.

Fanale, F.P., and J.R. Salvail (1984). "An Idealized Short-Period Comet Model: Surface Insolation, H_2O Flux, Dust Flux and Mantle Evolution," Icarus 60, 476–511.

Fanale, F.P., and J.R. Salvail (1987). "The Loss and Depth of CO_2 Ice in Comet Nuclei," Icarus 72, 535–554.

Fanale, F.P., and J.R. Salvail (1990). "The Influence of CO Ice on the Activity and Near Surface Differentiation of Comet Nuclei," Icarus 84, 403–413.

Feldman, P.D., M.F. A'Hearn, M.C. Festou, L.A. McFadden, H.A. Weaver and T.N. Woods (1986). "Is CO_2 Responsible for the Outbursts of Comet Halley?", Nature 324, 433–436.

Feldman, P.D., and W.H. Brune (1976). "Carbon Production in Comet West 1975n," Astrophys. J. 209, L45–L48.

Feldman, P.D, M.C. Festou, M.F. A'Hearn, C. Arpigny, P.S. Butterworth, C.B. Cosmovici, A.C. Danks, R. Gilmozzi, W.M. Jackson, L.A. McFadden, P. Patriarchi, D.G. Schleicher, G.P. Tozzi, M.K. Wallis, H.A. Weaver, and T.N. Woods (1987). "IUE Observations of Comet P/Halley: Evolution of the Ultraviolet Spectrum Between September 1985 and July 1986," Astron. Astrophys. 187, 325–328.

Feldman, P.D., P.Z. Takacs, and W.G. Fastie (1974). "Rocket Ultraviolet Spectro-photometry of Comet Kohoutek (1973f)," Science 185, 705–707.

Festou, M.C., J. Lecacheux, J.L. Kohl, T. Encrenaz, J. Baudrand, M. Combes, R. Despiau, P. Laques, O. Le fèvre, J.P. Lemonnier, G. Lelièvre, G. Mathez, M. Pierre, and J.L. Vidal (1986). "Photometry and Activity of the Nucleus of P/Halley at Heliocentric Distances Larger than 4.6 AU, Pre-Perihelion," Astron. Astrophys. 169, 336–344.

Green, D.W.E. (1989). Private communication.

Green, D. W. E., and C. S. Morris (1987). "The Visual Brightness Behavior of P/Halley During 1981–1987," Astron. Astrophys. 187, 560-568.

Greenberg, J.M. (1977). "From Dust to Comets," in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, ed. A.H. Delsemme, University of Toledo, Toledo, Ohio, pp. 491–497.

Greenberg, J.M. (1982). "What Are Comets Made of? A Model Based on Interstellar Dust," in Comets, ed. L.L. Wilkening, University of Arizona Press, Tucson, Arizona, pp. 131–163.

Greenberg, J.M. (1987). "Comet Halley: A Carrier of Interstellar Dust Chemical Evolution," Adv. Space Res. 7, No. 5, 33–44.

Greenberg, J.M., R. Grim, and L. van IJzendoorn (1986). "Interstellar S_2 in Comets," in Asteroids, Comets, and Meteors, II, eds. C.-I. Lagerkvist, B.A. Lindblad, H. Lundstedt and H. Rickman, Uppsala, pp. 225–227.

https://doi.org/10.1017/S0252921100109868 Published online by Cambridge University Press

Greenstein, J.L. (1962). "The Spectrum of Comet Humason (1961e)," Astrophys. J. 136, 688–690.

Grim, R.J.A., and J.M. Greenberg (1987). "Photoprocessing of H_2S in Interstellar Grain Mantles as an Explanation for S_2 in Comets," Astron. Astrophys. 181, 155–168.

Hanner, M.S., and R.L. Newburn (1989). "Infrared Photometry of Comet Wilson (1986l) at Two Epochs," Astron. J. 97, 254–261.

Hartmann, W.K., D.J. Tholen, and D.P. Cruikshank (1987). "The Relationship of Active Comets, 'Extinct' Comets, and Dark Asteroids," Icarus 69, 33–50.

Hartmann, W.K., D.J. Tholen, K.J. Meech, and D.P. Cruikshank (1989). "2060 Chiron: Colorimetry and Cometary Behavior," Icarus 83, 1–15.

Horanyi, M., T.I. Gombosi, T.E. Cravens, A. Korosmezey, K. Kecskemety, A.F. Nagy, and K. Szego (1984). "The Friable Sponge Model of a Cometary Nucleus," Astrophys. J. 278, 449–455.

Houpis, H.L.F., and D.A. Mendis (1981). "Dust Emission From Comets at Large Heliocentric Distances," Moon and Planets 25, 397–412.

Houpis, H.L.F., W.-H. Ip, and D.A. Mendis (1985). "The Chemical Differentiation of the Cometary Nucleus: The Process and its Consequences," Astrophys. J. 295, 654–667.

Hughes, D.W. (1975). "Cometary Outbursts, A Brief Survey," Quar. J. R. Astr. Soc. 16, 410–427.

Jewitt, D., and K.J. Meech (1986). "Cometary Grain Scattering Versus Wavelength or 'What Color is Comet Dust?'," Astrophys. J. 310, 937–952.

Jewitt, D., and K.J. Meech (1988). "The Absence of a Color-Distance Trend in Comets," Astron. J. 96, 1723–1730.

Johnson, R.E., J.F. Cooper, L.J. Lanzerotti, and G. Strazzulla (1987). "Radiation Formation of a Non-Volatile Comet Crust," Astron. Astrophys. 187, 889–892.

Keller, H.U., W.A. Delamere, W.F. Huebner, H.J. Reitsema, H.U. Schmidt, F.L. Whipple, K. Wilhelm, W. Curdt, R. Kramm, N. Thomas, C. Arpigny, C. Barbieri, R.M. Bonnet, S. Cazes, M. Coradini, C.B. Cosmovici, D.W. Hughes, C. Jamar, D. Malaise, K. Schmidt, W.K.H. Schmidt, and P. Seige (1987). "Comet P/Halley's Nucleus and Its Activity," Astron. Astrophys. 187, 807–823.

Klinger, J. (1980). "Influence of a Phase Transition of Ice on the Heat and Mass Balance of Comets," Science 209, 271–272.

Klinger, J. (1981). "Some Consequences of a Phase Transition of Water Ice on the Heat Balance of Cometary Nuclei," Icarus 47, 320–324.

Krankowsky, D.P. Lämmerzahl, I. Herrwerth, J. Woweries, P. Eberhardt, U. Dolder, U. Herrmann, W. Schulte, J.J. Berthelier, J.M. Illiano, R.R. Hodges, and J.H. Hoffman (1986). " In Situ Gas and Ion Measurements at Comet Halley," Nature 321, 326–329.

Kresák, L. (1977). "An Alternate Interpretation of the Oort Cloud of Comets?,"in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, ed. A.H. Delsemme, University of Toledo, Toledo, Ohio, pp. 93–97.

Kresák, L. (1979). "Dynamical Interrelations Among Comets and Asteroids," in Asteroids, ed. T. Gehrels, Univ. of Arizona Press, Tucson, AZ, 289–309.

Kronk, G.W. (1984). Comets, A Descriptive Catalog, Enslow Pub., Inc., Hillside, N.J.

Marsden, B.G. (1970). "On the Relationship Between Comets and Minor Planets," Astron. J. 75, 206–217.

Marsden, B.G. (1986). Catalog of Cometary Orbits, IAU Central Bureau for Astronomical Telegrams, SAO, Cambridge, MA.
Marsden, B.G. (1990a). "Comet Austin (1989c_1)," IAU Circ. No. 4972.
Marsden, B.G. (1990b). "Comet Austin (1989c_1)," IAU Circ. No. 4985.
Marsden, B.G., and Z. Sekanina (1973). "On the Distribution of 'Original' Orbits of Comets of Large Perihelion Distance," Astron. J. 78, 1118–1124.
Marsden, B.G., Z. Sekanina, and E. Everhart (1978). "New Osculating Orbits for 110 Comets and Analysis of Original Orbits for 200 Comets," Astron. J. 83, 64–71.
Marsden, B.G., Z. Sekanina, and D.K. Yeomans (1973). "Comets and Nongravitational Forces. V.," Astron. J. 78, 211–225.
Meech, K.J. (1988a). "Comet Wilson (1986l)," IAU Circ. No. 4552.
Meech, K.J. (1988b). "Distant, Active Comets Observable From the Southern Hemisphere," in Progress and Opportunities in Southern Hemisphere Optical Astronomy—Proceedings of the CTIO 25th Anniversary Celebration, eds. V.M. Blanco and M.M. Phillips, A.S.P. Conf. Series 1, 335–341.
Meech, K.J., and M.J.S. Belton (1989). "(2060) Chiron," IAU Circ. No. 4770.
Meech, K.J., and M.J.S. Belton (1990). "The Atmosphere of 2060 Chiron," Astron. J., submitted.
Meech, K.J., and D.C. Jewitt (1987). "Observations of Comet Bowell at Record Heliocentric Distance," Nature 328, 506–509.
Meech, K.J., D. Jewitt, and G.R. Ricker (1986). "Early Photometry of Comet P/Halley: Development of the Coma," Icarus 66, 561–574.
Mendis, D.A., and G.D. Brin (1977). "Monochromatic Brightness Variations of Comets. II. Core-Mantle Model," Moon 17, 359–372.
Mendis, D.A., and G.D. Brin (1978). "On the Monochromatic Brightness Variations of Comets," Moon and Planets 18, 77–89.
Moore, M.H., B. Donn, R. Khanna, and M.F. A'Hearn (1983). "Studies of Proton-Irradiated Cometary-Type Ice Mixtures," Icarus 54, 388–405.
Mumma, M.J. (1989). "Probing Solar System Objects at Infrared Wavelengths," Infrared Physics 29, 167–174.
Mumma, M.J., W.E. Blass, H.A. Weaver, and H.P. Larson (1988). "Measurements of the Ortho-Para Ratio and Nuclear Spin Temperature of Water Vapor in Comets Halley and Wilson (1986l) and Implications for Their Origin and Evolution," Bull. Amer. Astron. Soc. 20, 826.
Mumma, M.J., W.E. Blass, H.A. Weaver, and H.P. Larson (1990). "Measurements of the Ortho-Para Ratio and Nuclear Spin Temperature of Water Vapor in Comets Halley and Wilson (1986l) and Implications for Their Origin and Evolution," STSI Conf. on Origins and Evolution of Planetary Systems, in press.
Mumma, M.J., H.A. Weaver, and H.P. Larson (1987). "The Ortho-Para Ratio of Water Vapor in Comet P/Halley," Astron. Astrophys. 187, 419–424.
Mumma, M.J., H.A. Weaver, H.P. Larson, D.S. Davis, and M. Williams (1986). "Detection of Water Vapor in Halley's Comet," Science 232, 1523–1528.
Newburn, R.L., and H. Spinrad (1989). "Spectrophotometry of 25 Comets: Post-Halley Update for 17 Comets Plus New Observations for Eight Additional Comets," Astron. J. 97, 552–569.
Oikawa, S., and E. Everhart (1979). "Past and Future Orbit of 1977 UB, Object Chiron," Astron. J. 84, 134–139.

Oort, J.H. (1950). "The Structure of the Cloud of Comets Surrounding the Solar System, and a Hypothesis Concerning its Origin," Bull. Astron. Inst. Neth. Vol. 11, No. 408, 91–110.

Oort, J.H., and M. Schmidt (1951). "Differences Between New and Old Comets," Bull. Astron. Inst. Neth. Vol. 11, No. 419, 259–269.

Palmer, P., I. de Pater, and L.E. Snyder (1989). "VLA Observations of the OH Emission From Comet Wilson (1986l): The Value of High Resolution in Both Spatial and Velocity Coordinates," Astron. J. 97, 1791–1797.

Patashnick, H., G. Rupprecht, and D.W. Schuerman (1974). "Energy Source for Comet Outbursts," Nature 250, 313–314.

Prialnik, D., and A. Bar-Nun (1987). "On The Evolution and Activity of Cometary Nuclei," Astrophys. J. 313, 893–905.

Rickman, H. (1985). "Interrelations Between Comes and Asteroids," in Dynamics of Comets: Their Origin and Evolution, IAU Colloquium No. 83, eds. A. Carusi, and G.B. Valsecchi, D. Reidel Pub. Co., Dordrecht, pp. 149–172.

Roemer, E. (1962). "Activity in Comets at Large Heliocentric Distance," Pub. Astron. Soc. Pacific 74, 351–365.

Roettger, E.E., and P.D. Feldman (1990). "Comet Austin ($1989c_1$)," IAU Circ. No. 4934.

Roettger, E.E., P.D. Feldman, M.F. A'Hearn, M.C. Festou, L.A. McFadden, and R. Gilmozzi (1989). "IUE Observations of the Evolution of Comet Wilson (1986l): Comparison With P/Halley," Icarus 80, 303–314.

Sandford, S.A., and L.J. Allamandola (1988). "The Condensation and Vaporization Behavior of H_2O:CO Ices and Implications for Interstellar Grains and Cometary Activity," Icarus 76, 201–224.

Schleicher, D.G., D.J. Osip, and P.V. Birch (1990). "Comet Austin ($1989c_1$)," IAU Circ. No. 4983.

Scholl, H. (1979). "History and Evolution of Chiron's Orbit," Icarus 40, 345–349.

Sekanina, Z. (1973). "Existence of Icy Comet Tails at Large Distance From the Sun," Astrophys. Lett. 14, 175–180.

Sekanina, Z. (1975). "A Study of the Icy Tails of the Distant Comets," Icarus 25, 218–238.

Sekanina, Z. (1979). "Fan-Shaped Coma, Orientation of Rotation Axis, and Surface Structure of a Cometary Nucleus I. Test of a Model on Four Comets," Icarus 37, 420–442.

Sekanina, Z. (1982a). "The Problem of Split Comets in Review," in Comets, ed. L.L. Wilkening, University of Arizona Press, Tucson, Arizona, pp. 251–287.

Sekanina, Z. (1982b). "Comet Bowell (1980b): An Active-Looking Dormant Object?", Astron. J. 87, 161–169.

Sekanina, Z. (1988). "Comet Wilson (1986l)," IAU Circ. No. 4557.

Sekanina, Z. (1990). "Comet Austin ($1989c_1$)," IAU Circ. No. 4977.

Smoluchowski, R. (1981). "Heat Content and Evolution of Cometary Nuclei," Icarus 47, 312–319.

Smoluchowski, R. (1985). "Amorphous and Porous Ices in Cometary Nuclei," in Ices in the Solar System, eds. J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski, NATO Adv. Sci. Inst. Series C, Vol. 156, D. Reidel Pub. Co., Dordrecht, pp. 397–406.

Smoluchowski, R. (1986). "Brightness Curve and Porosity of Cometary Nuclei," in Asteroids, Comets, and Meteors, II, eds. C.-I. Lagerkvist, B.A. Lindblad, H. Lundstedt and H. Rickman, Uppsala, pp. 305–315.
Smoluchowski, R. (1989). "Properties of Mantles on Cometary Nuclei," Astron. J. 97, 241–245.
Stern, S.A. (1988). "Collisions in the Oort Cloud," Icarus 73, 499–507.
Stern, S.A. (1989a). "ISM-Induced Erosion and Gas-Dynamical Drag in the Oort Cloud," Icarus 84, 447–466.
Stern, S.A. (1989b). "Implications of Volatile Release From Object 2060 Chiron," Pub. Astr. Soc. Pac. 101, 126–132.
Stern, S.A., and J.M. Shull (1988). "The Influence of Supernovae and Passing Stars on Comets in the Oort Cloud," Nature 332, 407–411.
Svoren, J. (1983). "Photometric Observations of Long Period Comets at Large Heliocentric Distances in the Years 1861 to 1925," Contributions of the Astron. Obs. Skalnaté Pleso 11, 95–123.
Svoren, J. (1984). "Photometric Observations of Long Period Comets at Large Heliocentric Distances in the Years 1927 to 1955," Contributions of the Astron. Obs. Skalnaté Pleso 12, 7–44.
Svoren, J. (1985). "Photometric Observations of Long Period Comets at Large Heliocentric Distances in the Years 1956–1976," Contributions of the Astron. Obs. Skalnaté Pleso 13, 93–125.
Svoren, J. (1986). "Variations of Photometric Exponents of Long-Period Comets at Large Heliocentric Distances," in Asteroids, Comets, and Meteors, II, eds. C.-I. Lagerkvist, B.A. Lindblad, H. Lundstedt and H. Rickman, Uppsala, pp. 323–326.
Tholen, D.J., W.K. Hartmann, and D.P. Cruikshank (1988). "2060 Chiron," IAU Circ. No. 4554.
Tokunaga, A.T., W.F. Golisch, D.M. Griep, C.D. Kaminski, and M.S. Hanner (1988). "The NASA Infrared Telescope Facility Comet Halley Monitoring Program II. Postperihelion Results," Astron. J. 96, 1971–1976.
Weissman, P.R. (1979). "Nongravitational Perturbations of Long-Period Comets," Astron. J. 84, 580–584.
Weissman, P.R. (1982). "Dynamical History of the Oort Cloud," in Comets, ed. L.L. Wilkening, University of Arizona Press, Tucson, Arizona, pp. 637–658.
Weissman, P.R. (1986). "The Oort Cloud and the Galaxy: Dynamical Interactions," in The Galaxy and the Solar System, eds. R. Smoluchowski, J.N. Bahcall, and M.S. Matthews, University of Arizona Press, Tucson, Arizona, pp. 204–237.
Weissman, P.R. (1987). "Post-Perihelion Brightening of Comet P/Halley: Springtime for Halley," Astron. Astrophys. 187, 873–878.
Weissman, P.R. (1990). "The Oort Cloud," Nature 344, 825–830.
Weissman, P.R., and S.A. Stern (1989). "Physical Processing of Cometary Nuclei," submitted to Proc. of the Workshop on Analysis of Returned Comet Nucleus Samples, Milpitas, CA.
Weissman, P.R., M.F. A'Hearn, L.A. McFadden, and H. Rickman (1989). "Evolution of Comets Into Asteroids," in Asteroids II, eds. R. Binzel, T. Gehrels, and M.S. Matthews, University of Arizona Press, Tucson, Arizona, pp. 880–920.
West, R.M. (1990). "Post-Perihelion Observations of Comet Halley. II (R = 10.1 AU)," Astron. Astrophys. 228, 531–538.

West, R.M., and H.E. Jørgensen (1990). "Post Perihelion Observations of Comet Halley at R = 8.5 AU," Astron. Astrophys. 218, 307–316.
Whipple, F.L. (1950). "A Comet Model. I. The Acceleration of Comet Encke," Astrophys. J. 111, 375–394.
Whipple, F.L. (1977). "The Constitution of Cometary Nuclei," in Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins, ed. A.H. Delsemme, University of Toledo, Toledo, Ohio, pp. 25–35.
Whipple, F.L. (1978). "Cometary Brightness Variation and Nucleus Structure," Moon and Planets 18, 343–359.
Whipple, F.L. (1989). "Comets in the Space Age," CFA Preprint Series No. 2707, Astrophys. J., submitted.
Woods, T.N., P.D. Feldman, K.F. Dymond, and D.J. Sahnow (1986). "Rocket Ultraviolet Spectroscopy of Comet Halley and Abundance of Carbon Monoxide and Carbon," Nature 324, 426–438.
Wyckoff, S., M. Wagner, P.A. Wehinger, D.G. Schleicher, and M.C. Festou (1985). "Onset of Sublimation in Comet P/Halley (1982i)," Nature 316, 241–242.