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Activity in Distant Comets

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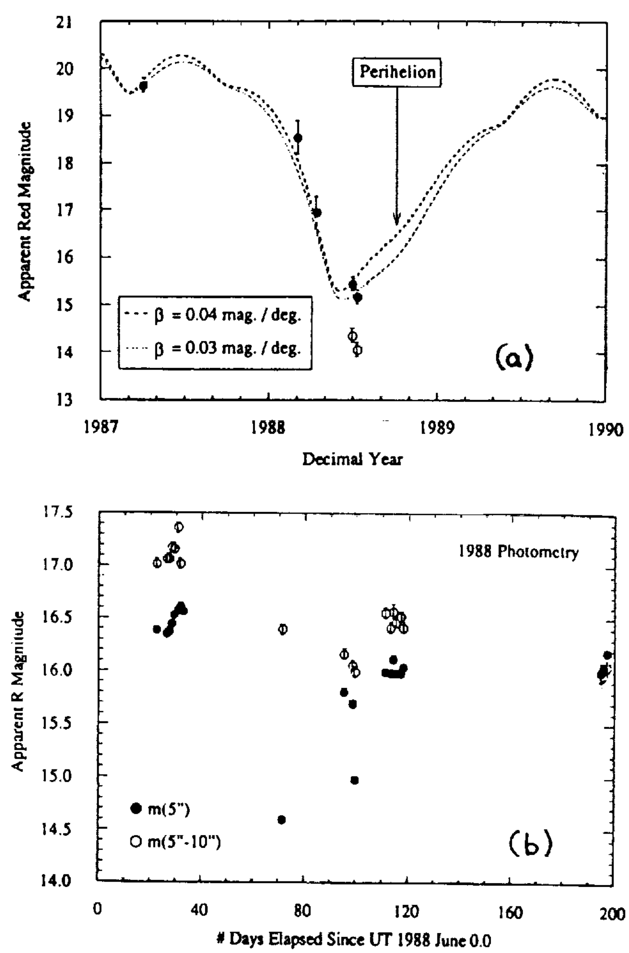
Abstract. Activity in distant comets remains a mystery in the sense that we still have no complete theory to explain the various types of activity exhibited by different comets at large distances. This paper will explore the factors that should play a role in determining activity in a distant comet, especially in the cases of comet P/Tempel 2, comet Schwassmann-Wachmann 1 (hereafter SW1), and 2060 Chiron.

1. Introduction

From the 1988 observing campaign on Tempel 2, we know that this comet is essentially asteroidal (photometrically and visually) at heliocentric distance $R \geq 2.3$ AU (Jewitt and Luu 1989). The long term photometric behavior of Tempel 2 is illustrated in Fig. 1a, where a plot of the cometary magnitude vs. the date of observation is presented. The two lines represent the inverse-square ("asteroidal") law for a phase-darkened nucleus for two different phase coefficients. Except for the data points represented by the hollow dots (which were measured after a resolved coma had been observed around the comet), the asteroidal models provide a very good fit to the photometry, proving that Tempel 2 was indeed a bare nucleus at these distances.



SW1, on the other hand, has never been observed in a bare nucleus state in spite of its large semimajor axis (~ 6 AU). In his extensive two-year study of the comet, Jewitt (1990) reported that SW1 displayed an extended coma on all dates of observation. The persistent coma is different from the impulsive outburts for which SW1 is famous (Whipple 1980). Fig. 1b shows the nightly mean magnitudes of SW1 measured in two different apertures and monitored over 7 months in 1988. The Figure shows outbursts (e.g., day numbers 71 and 99) superimposed on the steady coma.

Fig. 1. a) Mean R magnitudes of Tempel 2 vs. the epoch of observation. Solid dots denote nucleus magnitudes; hollow dots denote magnitudes within a 20"-radius aperture. The 2 lines show the "asteroidal model" with 2 different phase coefficients (from Jewitt and Luu 1988). b) Mean R magnitudes of SW1 vs. the date of observation in 1988. *m(5")* is the magnitude measured within a 5"-radius aperture, while *m(5"-10")* is the annular magnitude within the inner and outer radius 5" and 10", respectively (from Jewitt 1990).

Chiron differs from both Tempel 2 and SW1 in that it exhibits a resolved coma at the unusually large distance $R \sim 12$ AU (Hartmann *et al.* 1990), although non-asteroidal photometric behavior has been observed since 1988 (Tholen *et al.* 1988). A graphical summary of the photometric behavior of Chiron is shown in Fig. 2, where I have plotted all the photometry known to me up to 1990. The years 1980 - 87 represent a faint state, whereas in 1988 - present, Chiron is up to a magnitude brighter.

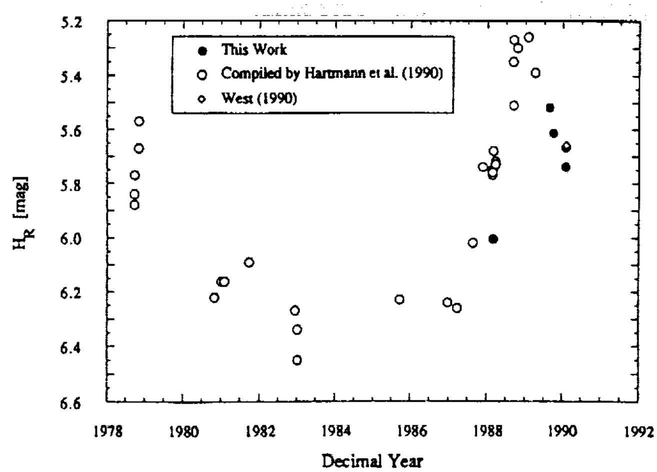


Fig. 2. Integrated photometry of Chiron reduced to red absolute magnitudes and plotted as a function of the date of observation. The data compiled from Hartmann *et al.* (1990) were transformed from H_V to H_R by $H_R = H_V - 0.37$. Errors are generally too small to be seen at the scale of the plot (from Luu and Jewitt 1990).

2. Tempel 2 vs. SW1

In Fig. 3, we plot the specific mass loss rate of crystalline water ice, $Z_{water\ ice}$, of comets Tempel 2 and SW1 as a function of R. (Chiron is excluded from the plot since its activity occurs beyond the distance range where water sublimation is feasible). At small R (≤ 2 AU), $Z_{Tempel\ 2}$ is 100 - 10000 times larger than Z_{SW1}, but drops to an insignificant level at larger R, even well within the water sublimation zone (nominally ≤ 5 AU for most comets).

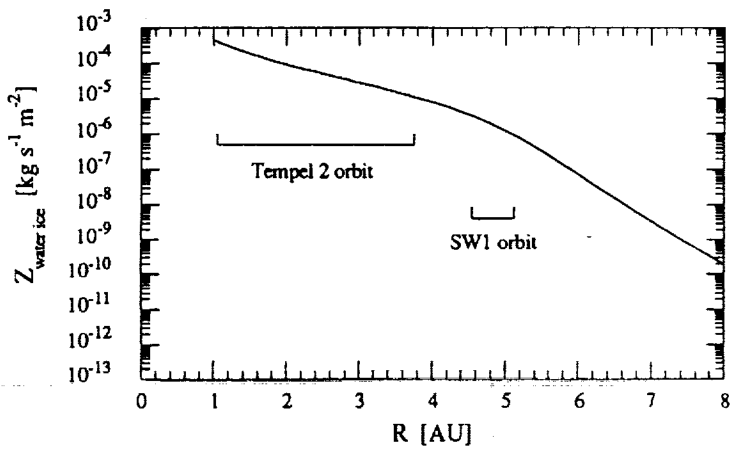


Fig. 3. The specific mass loss rate of crystalline water ice, $Z_{water\ ice}$, for Tempel 2 and SW1 plotted as a function of R. Both comets are assumed to have an albedo of 0.05, and conduction into the interior is ignored. $Z_{water\ ice}$ for Tempel 2 is about 100 - 10000 times larger than $Z_{water\ ice}$ for SW1.

Why is Tempel 2 a bare nucleus while SW1 shows an extensive coma at 5 AU? Several factors are likely to play a role:

1) The size of the active area. The idea of an inert mantle formed by particles that are too heavy to escape from the nucleus is now established and firmly proven by observations (e.g., Keller 1990). The basic parameters of cometary activity in Tempel 2, SW1 and Chiron are listed in Table 1. The fractional active areas F_{active} on SW1 and Tempel 2 are comparable (~ 1%), but since SW1 is much larger than Tempel 2, the absolute active area

A_{active} of SW1 is 100 times larger than that of Tempel 2.

Table 1. Activity Parameters

Comet	Radius [km]	F_{active}	A_{active} [m^2]
P/Tempel 2	5	0.1 - 1%	(0.6 - 6) x 10^6
P/SW1	~ 20	2%	10^8
2060 Chiron	60 - 150	10^{-3} - 10^{-5}%	10^4 - 10^6

2) Spin axis and rotation period. If a comet rotates very slowly or is insolated pole-on (the spin axis pointing at the Sun), the surface temperature can stay sufficiently high for sublimation to take place even at large distances like 5 AU. The rotational properties of SW1 are unknown but both Whipple (1980) and Jewitt (1990) showed some evidence that SW1 is a very slow rotator (rotation period ≥ 5 days).

3) Interior volatiles. By the nature of its orbit, Tempel 2 has been thoroughly heated by the Sun and thus may have an interior consisting largely of crystalline ice instead of amorphous ice (the metastable form of ice that exists before turning into crystalline ice at ~ 150 K. SW1 is large, on a nearly circular orbit (eccentricity ~ 0.04), thus its interior should still retain a large fraction of amorphous ice. It is likely that the interior ice inventory would affect sublimation at the surface.

4) Mantle structure. At least two mantle-forming processes are known: a) due to left-over grains that were too heavy to escape from the nucleus, and b) due to cosmic ray bombardment, whether in the Oort cloud or Kuiper belt. Again, since SW1 has not been subjected to intense solar heating like Tempel 2, it might retain more of its cosmic ray-induced crust than Tempel 2. It is not known how such a mantle affects sublimation as compared to a mantle formed by left-over large grains.

3. Chiron

Chiron is distinguished from other short-period comets by its large size (radius ≤ 150 km) and large semimajor (~12 AU). As mentioned above, factors such as the large size and mantle structure are likely to influence the amount of cometary activity on Chiron. With such a large nucleus, not much area is needed before a detectable coma is generated. Chiron's activity also cannot be caused by water ice, and is reminiscent of activity in other distant comets such as comet Halley (~15 AU, Hainaut *et al.* 1991) and Bowell (~14 AU, Meech and Jewitt 1987). At such large distances, materials more volatile than water ice have to be responsible for cometary activity, such as CO and CO_2 (Luu and Jewitt 1990).

In particular, the mantle of Chiron may differ from that of other short-period comets by the size distribution of its mantle grains, and by the fact that it is likely to be entering the inner Solar System for the first time (Hahn and Bailey 1990). The size distribution of mantle grains is determined by the volatiles that sublimate and eject dust grains through gas drag. The more volatile materials responsible for activity on Chiron should leave behind on the surface a size distribution of grains that is different from those left behind by water ice, the driving volatile in common short-period comets. Furthermore, if Chiron is making its first voyage inward to the Sun, its mantle is likely to be mainly caused by cosmic ray bombardment, which might produce a non-volatile crust capable of surviving a few passages in the inner Solar System (Strazzula *et al.* 1983). The cosmic-ray induced mantle (as opposed to the mantle formed by large heavy grains) may explain why the dynamically new comets seem to be more active than the short-period comets at comparably large distances.

The last possible cause of activity at large distances that I will mention is electrostatic charging of the nucleus. Mendis *et al.* (1981) have shown that electric currents, generated by solar wind ions and UV radiation, can electrostatically charge the nucleus surface, causing levitation and subsequent expulsion of loose, submicron-sized dust from the surface. This process may apply to small comets where the escape velocity is relatively small.

4. Conclusion

As Tempel 2, SW1 and Chiron have exemplified, activity in distant comets can take on quite distinct flavors whether in the form of a bare nucleus or continuous activity. However, the ubiquitous mantle has emerged as an increasingly important factor in controlling the activity on cometary surfaces, and our understanding of its physical properties is still woefully lacking. Until the surface and interior of the nucleus are better understood, a simplistic conclusion that can be reached thus far is the following: if we assume that all comets formed basically in the same manner, 3 major factors are likely to influence the types of cometary activity at large distances: a) the size of the nucleus, b) the rotation period and pole direction of the comet, and c) the details of its thermal history, as caused by its dynamical history.

Acknowledgments

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