sediment (although the organisms in this experiment were in sediment equal to 12 percent of the original amount) respire at a higher rate than those in natural sediment, especially when densely packed together (*8*). Their true undisturbed aerobic respiration is probably closer to half the rate shown in this experiment.

The amount of heat produced and rate of heat production by sediments are clearly insignificant in the total heat budget of the mud flat; that is, in comparison with the daily solar heating, nighttime cooling, and tidal heat transport. The heat itself is of no apparent ecological consequence. It is our eventual understanding of the processes that generate this heat that is important in ecology.

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Visibility of Comet Nuclei

Abstract. *Photography of the nucleus of comet Halley is the goal of several planned space missions. The nucleus of a comet is surrounded by a cloud of dust particles. If this cloud is optically thick, it will prevent observation of the nuclear surface. Broadband photometry of nine comets has been analyzed to determine the visibility of their nuclei. Only in the case of comet West near perihelion was the dust dense enough to interfere with imaging. Comparison of the visual brightness of the well-observed comets with that of Halley in 1910 leads to the conclusion that the nucleus of Halley can be imaged without significant obscuration by the dust.*

A number of international efforts are in the planning stage for the study of comet Halley, which is expected to reach perihelion in February 1986. Space missions could carry cameras close enough to photograph the nucleus of this comet. However, it is not clear that the dust coma will be optically thin enough to reveal the nucleus. Direct observation of the nucleus is important since it can distinguish between the generally accepted view that the nucleus of a comet is a mixture of ices and dust, as originally suggested by Whipple (*1*), and a minority view espoused by Lyttleton (*2*), that there is no nucleus, only a swarm of particles. In the Whipple model the gas produced by the sublimation of ices carries the dust grains away from the nucleus to produce the coma and dust tail. The sublimation of cometary ice is not likely to be uniform over the surface, and spacecraft imagery may reveal active areas or "jets" that are responsible for the nongravitational forces on comets (*3*). It is shown here that broadband infrared and visual observations can be used to obtain useful estimates of the optical depth τ of the dust shell without extensive modeling of the dust or coma.

Broadband observations over the wavelength, λ, range from 0.5 to 18 μm have been obtained for nine comets during the last decade. These data may be used to calculate the optical depth of the dust in the comae of these comets. Consider the case of comet West. Figure 1 shows the power distribution for comet West on 24.8 February 1976. The short-wavelength radiation is primarily scattered sunlight, and the long-wave radiation is thermal radiation from the dust grains. The short-wave data are fit by a 6000 K blackbody appropriate for the scattered sunlight; the long-wave data can be represented by a 880 K blackbody with a superimposed silicate excess.

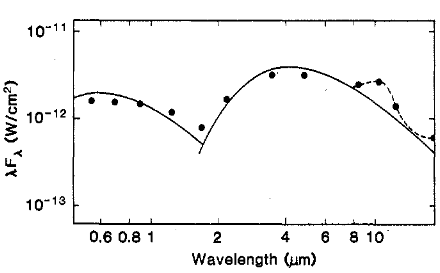

Fig. 1. Observed power distribution of comet West on 24.8 February 1976.

This 10-μm excess is due to the presence of small silicate grains of radius approximately 1 μm (*4*). In Fig. 1 log λF_λ is plotted against log λ. For a blackbody on such a plot, the power flux is given by $F = 1.36\ (\lambda F_\lambda)_{max}$ W/cm^2. In the case of comet West, the energy received in the visual is 2.58×10^{-12} W/cm^2 and in the infrared is 5.44×10^{-12} W/cm^2. The ratio of the energy in the visual to that in the infrared is 0.47, and the albedo at this scattering angle is $0.47/1.47 = 0.32$. The comet dust shows strong forward scattering and the bolometric Bond albedo for comet West is between 0.3 and 0.5 (*5*).

The long-wave thermal emission is from small grains, for which the infrared emission efficiency is proportional to their radius. As a consequence, the infrared luminosity depends on the mass of the grains in the observed geometry and is independent of particle size. The relation between emission efficiency, grain radius, and temperature depends on the optical properties of the grain material. An expression for the total observed grain mass has been derived (*6*) and is given by

$$M = 1.7 \times 10^{35} \frac{(\lambda F_\lambda)_{max}\, \Delta^2}{T^4} \qquad (1)$$

where $(\lambda F_\lambda)_{max}$ is the infrared value in watts per square centimeter, Δ is the earth-comet distance in astronomical units (1 AU = 1.5×10^8 km), and T is the grain temperature in kelvins. Using $T = 880$ K, $(\lambda F_\lambda)_{max} = 4 \times 10^{-12}$ W/cm^2; and $\Delta = 0.85$ AU leads to a mass of 9.6×10^{11} g. The mass loss rate may be obtained by dividing the mass by the residence time, or the time for a dust grain to travel a linear distance determined by the angular radius of the observing diaphragm, which is 10 arc seconds in this case. The velocity of the dust leaving the nucleus is approximately sonic in the gas, or about 0.5 km/sec (*7*). The residence time is therefore approximately 10^4 seconds and the mass loss rate 7×10^7 g/sec. The optical depth produced by the outflowing dust can be estimated from detailed models, which must make assumptions about the grain size distribution and the optical properties of the dust.

There is, however, a more direct approach to determining the optical depth. It has been demonstrated by observations with diaphragms of radius 5 arc seconds to 1 arc minute that the value of $(\lambda F_\lambda)_{max}$ is proportional to diaphragm radius (*8–10*). This is expected for dust that leaves the nucleus at a fixed velocity and subsequently satisfies the continuity equation (the dust flows freely with no creation or annihilation of the grains).

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Table 1. Properties of the dust comae of comets West and Kohoutek.

Comet	Date	r (AU)	Δ (AU)	$(\lambda F_\lambda)_{max}$ (W/cm²)	Temperature (K)	δ (arc sec)	θ_{BB} (arc sec)	θ_{crit} (arc sec)	R_{crit} (km)
West	24.8 February 1976	0.20	0.85	4×10^{-12}	880	10	0.261	6.8×10^{-3}	4.30
West	21.6 March 1976	0.81	1.05	2.2×10^{-14}	370	10	0.109	1.2×10^{-3}	0.95
Kohoutek	28.1 January 1974	0.15	1.09	1.5×10^{-12}	1000	13	0.124	1.2×10^{-3}	0.98
Kohoutek	29.7 December 1973	0.95	0.93	1×10^{-15}	360	13	0.025	5×10^{-5}	0.035

For any observing diaphragm the average optical depth is the ratio of the solid angle of the diaphragm to the solid angle of a blackbody, θ_{BB}, that would supply the same flux. The angular radius of the blackbody in arc seconds can be shown to be

$$\theta_{BB} = 1.01 \times 10^{11} \frac{(\lambda F_\lambda)_{max}^{1/2}}{T^2} \qquad (2)$$

For our case of comet West (Fig. 1), the blackbody angular radius is 0.26 arc second and $\tau = (0.26/10)^2 = 7 \times 10^{-4}$. It is therefore optically thin in the observing diaphragm. We can calculate the angular size at which τ becomes unity since $(\lambda F_\lambda)_{max}$ is proportional to the radius of the observing diaphragm. The construction is shown in Fig. 2 and $\tau = 1$ would be reached at 7×10^{-3} arc second. In this example $\tau = 1$ occurs at a linear radius of 4.3 km. The nucleus of comet West would be just visible through the dust if the radius were about 4 km.

The example above is an extreme case. West was a dusty comet and we chose an observation near perihelion at a heliocentric distance, r, of 0.2 AU. We can estimate τ as a function of r since dust production rate varies approximately as $1/r^2$ (*6*). Table 1 shows the result of the optical depth calculation for two well-observed comets, West and Kohoutek, near perihelion and near 1 AU. Here r and Δ are the comet-sun and comet-earth distances in astronomical units, δ is the angular radius of the observing diaphragm, $(\lambda F_\lambda)_{max}$ is the infrared power per unit area in watts per square centimeter, θ_{BB} is defined by Eq. 2, and θ_{crit} and R_{crit} are the corresponding angular and linear radii at $\tau = 1$. The equation relating the quantities is

$$\theta_{crit} = \frac{(\theta_{BB})^2}{\delta} \qquad (3)$$

The last column of Table 1 shows that only in the case of West at perihelion was the dust shell dense enough to interfere with imaging the nucleus.

This analysis can be applied to the case of comet Halley, which is expected to be much like comet West (*11*) in dust production and to have a nuclear radius of 5 to 15 km (*12*). Its perihelion distance is 0.6 AU. During the time the comet is at a heliocentric distance less than 1 AU, its geocentric distance will be between 0.8 and 1 AU. A nucleus 10 km in radius viewed from the earth would have an angular diameter of 0.03 arc second, too small to be photographed even with space telescopes.

We conclude that the critical radius at which the optical depth of the dust coma of a comet becomes unity can be estimated from infrared observation and can serve as a useful guide for assessing the observability of a comet nucleus from a spacecraft or space telescope. Imagery of the nucleus of a comet as active as West is possible at heliocentric distances down to several tenths of an astronomical unit. The dust production of comet Halley is expected to be in the range defined by West and Kohoutek, and therefore the nucleus could be imaged from a spacecraft with little interference from an opaque dust cloud. For comet Encke, which has a short period (3.3 years) and a dust production 100 times less than that of West, the dust interference problem would be minimal.

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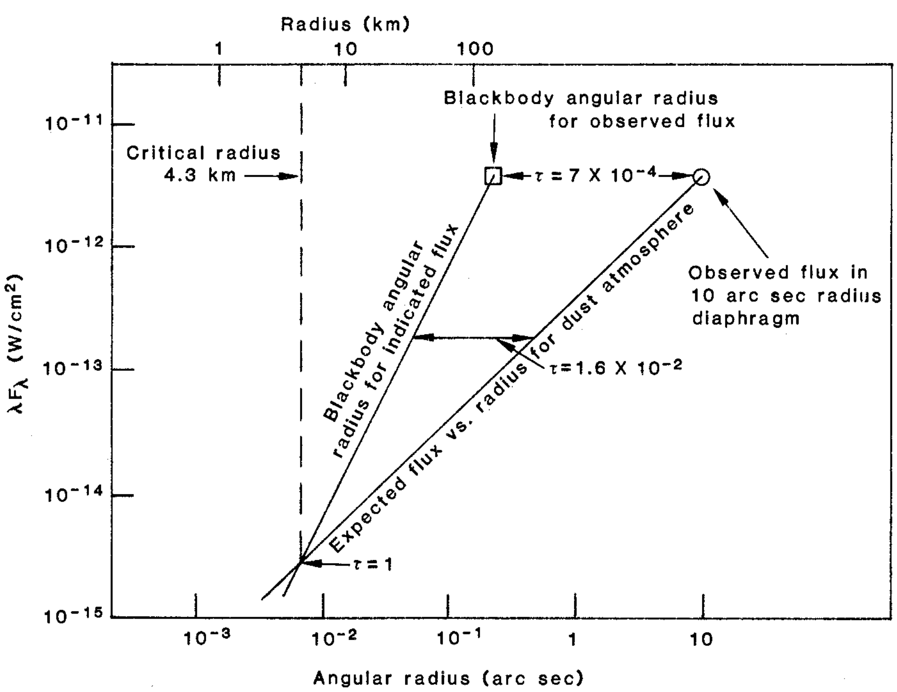

Fig. 2. Plot of $(\lambda F_\lambda)_{max}$ versus angular radius and linear radius at the comet for comet West near perihelion.

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10. R. Gehrz and E. P. Ney (unpublished results for comet Bradfield 1980i) find that the relation of flux proportional to diaphragm diameter applies in the angular diameter range of 5 to 25 arc seconds.
11. Comparison of comets in terms of visual magnitudes is uncertain at best. However, comet Halley in 1910 was 5.5 magnitudes corrected to $r = \Delta = 1$ AU and comet West was 6.3 magnitudes before perihelion and 5.8 magnitudes after perihelion under the same circumstances.
12. Estimates of nuclear diameters depend on the value assumed for the nuclear albedo. My estimate of radius 5 to 15 km can be compared with the diameter of 5 km given in D. K. Yoemans, *Comet Halley Handbook* (Publ. 400-911/81, Jet Propulsion Laboratory, Pasadena, Calif., 1981).
13. I thank T. W. Jones for discussions leading to the presentation in Fig. 2. I am also indebted to two anonymous referees for detailed and constructive comments. This research is supported by NASA grant NsG2014.

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