Sungrazing comets: Properties of nuclei and in-situ detectability of cometary ions at 1 AU

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Abstract

A one dimensional sublimation model for cometary nuclei is used to derive size limits for the nuclei of sungrazing comets, and to estimate oxygen ion fluxes at 1 AU from their evaporation. Given that none of the ≈ 300 sungrazers detected by the SOlar and Heliospheric Observatory (SOHO) was observed after disappearing behind the sun, and that small nuclei with a radius of ≈ 3.5 m could be observed, it is assumed that all SOHO sungrazers were completely destroyed. For the case that sublimation alone is sufficient for destruction, the model yields an upper size limit as a function of nuclear density ϱ, albedo A and perihelion distance q. If the density of the nuclei is that typical of porous ice ($600\,\mathrm{kg\,m^{-3}}$), the maximum size is 63 m. These results confirm similar model calculations by Weissman (1983). An analytical expression is derived that approximates the model results well. We discuss possible modifications of our results by different disruption mechanisms. While disruption by thermal stress does not change the upper size limits significantly, they may be somewhat increased by tidal disruption (up to 100 m for a density of $600\,\mathrm{kg\,m^{-3}}$) dependent on the isotropy of the sublimation process and the tensile strength of the comet. Implications for the Kreutz family of sungrazers are discussed.

Oxygen ions from the sublimation of sungrazing comets form a tail. Fluxes from this tail are sufficiently high to be measured at 1 AU by particle detectors on spacecraft, but the duration of a tail crossing is only about half an hour. Therefore the probability of a spacecraft actually encountering a tail of an evaporating sungrazer is only of the order of two percent per year.

1 Introduction

Cometary nuclei are difficult to study. They cannot be spatially resolved from earth and whenever they come close to the sun they are surrounded by a coma which is several magnitudes brighter than the nucleus. The nucleus of comet P/Halley has been investigated **in situ** during the Giotto fly-by in 1986, allowing an accurate determination of its size, shape, and albedo (Keller et al. 1987). However, the mass of P/Halley could not be determined with sufficient accuracy to derive meaningful constraints on the density of the comet (Peale 1989).

Other methods to estimate some properties of the cometary nucleus like size and albedo are remote observations of comets far from the sun (e.g. Hainaut et al. 1995) and interpretation of properties of the coma in observations at high spatial resolution (e.g. Weaver et al. 1997). These observations do not reveal any information about the density, material strength or internal structure of comets.

Additional properties of cometary nuclei are revealed indirectly when comets are disrupted. Up to 1996, 33 split comets have been observed (Sekanina 1997). Five of these comets are possibly split by tidal forces, in the other cases the cause of the disruption is unknown. Therefore the study of disruption physics and that of the physical nature of the cometary nucleus from cometary splittings in general is difficult.

The disruption of comet D/Shoemaker-Levy 9 during a close encounter with Jupiter and its subsequent collision with the planet has gained much attention. A large number of studies about the nature of the comet has been published, including the determination of the structure of its nucleus from tidal breakup (Asphaug and Benz (1996), see Noll et al. (1996) for an overview), but some controversy remains (Sekanina et al. 1998).

In this paper, we discuss the destruction of members of the Kreutz group of sungrazing comets, focussing on the about 300 comets recently detected by the SOlar and Heliospheric Observatory (SOHO). In a few cases bright comets close to the sun can be observed with the naked eye (a total of seven comets since 1880, e.g. the great September comet C/1882 R1, comet Pereyra 1963 R1, and comet Ikeya-Seki 1965 S1). Some of these comets are observed to split into 2-4 fragments during perihelion passage. Much fainter members of the Kreutz comet group are detected by space-based coronographs. The Solar Maximum Mission (SMM) and the SOLWIND coronograph detected a total of 16 Kreutz comets between 1979 and 1989. The Large Angle and Spectrometric COronograph (LASCO) on SOHO, which is sensitive to still fainter objects, detected about 300 sungrazers between January 1996 and June 2001. Marsden (1989) showed from a detailed analysis of the orbits of the sungrazers known at the time that all of them are results of successive fragmentations of a common progenitor, maybe a bright comet which appeared in the year 371 BC.

None of the sungrazers discovered from space was observed after perihelion. The perihelia of most of them are between one and two solar radii, so they did not fall into the sun. The only available size estimate of a sungrazer observed by SOHO is from the Ly α intensity of C/1996 Y1 measured by the UltraViolet Coronograph Spectrometer on SOHO (Raymond et al. 1998). Its radius is only $\approx 3.5\,\mathrm{m}$ which means that objects with a diameter of a few meters are detectable.

We assume that the sungrazers observed from spacecraft are destroyed completely during their passage near the sun. One might argue that a comet which is depleted of its volatiles or covered by a refractory crust during its perihelion passage might be difficult to detect post-perihelion even if it survives its perihelion passage. But the detection of Fe I and Ni I emissions in spectra of the great September comet C/1882 R1 (Copeland and Lohse 1882) and the appearance of Na I, K I, Ca I, Ca II, Cr I, Co I, Mn I, Fe I, Ni I, Cu I, and V I in comet Ikeya-Seki at heliocentric distances below 0.2 AU (Preston 1967, Slaughter 1969) suggests that even the dust component of the nucleus will evaporate under the extreme conditions encountered by a sungrazing comet. Therefore we conclude that the sungrazers discovered from space did indeed not survive their perihelion passage.

This work is focused mainly on the question of what can be inferred from the complete destruction. Two processes can contribute to the destruction of the sungrazing comets detected by SOHO: sublimation and disruption. The size of the surface layer which sublimates during the perihelion passage of a sungrazing comet was first estimated analytically by Huebner (1967), who equated the energy sublimated by the sungrazer with the solar input energy. A more detailed numerical model which included thermal emission of the nucleus and heat conduction into the nucleus was published by Weissman (1983). Both models result in a few tens of meters for the size of the sublimating layer. Disruption mechanisms have so far not been discussed in the context of the destruction of sungrazing comets.

We calculate the maximum size of a sungrazer which is destroyed by sublimation alone with a numerical model similar to that by Weissman. A nucleus of pure water ice is assumed. We derive a semi-analytical approximation from our model which fits the numerical results from Weissman (1983) and the present work well. The implications of the porous nature of cometary water ice on the thickness of the sublimating layer are discussed.

We then study if sungrazers larger than the size limits for destruction by sublimation alone can be completely destroyed by a combination of sublimation and disruption. As a first candidate, we study tidal disruption. We show that the combination of sublimation and tidal disruption allows a complete destruction of nuclei larger than this limit only if sublimation is highly anisotropic. We also show that consideration of disruption by thermal stress does not change our upper limits significantly. Based on these results, implications for the Kreutz family of sungrazers and the nucleus of the progenitor are discussed.

Finally we consider the possibility of an *in situ* detection at 1 AU of ions from a sublimating sungrazing comet. We conclude that while expected fluxes are sufficiently high to be measurable, the probability of a spacecraft actually passing through such an ion cloud is only a few percent.

2 Model description

The model is restricted to the nucleus and does not include the coma. We assume that the nucleus is spherical and rotating sufficiently fast that all physical quantities are radially symmetric. The chemical composition is assumed to be 100 % H_2O ice. At the surface, the energy balance is expressed with

$$\frac{P_{\mathrm{sun}}(1-A)}{16\pi d^2} = \sigma T_{\mathrm{s}}^4 + Z(T_{\mathrm{s}}) \cdot L(T_{\mathrm{s}}) - F_{\mathrm{s}} \tag{1}$$

(e.g. Fernández and Jockers 1983). Here $P_{\mathrm{sun}} \approx 3.83 \cdot 10^{26}\,\mathrm{W}$ is the power of the sun, A the cometary albedo, d the heliocentric distance, σ the Stefan-Boltzmann-constant, T_{s} the surface temperature, $Z(T) = p(T) \cdot \sqrt{\mu/(2\pi T\,k)}$ the sublimation flux in $\mathrm{kg\,m^{-2}\,s^{-1}}$ (as derived by Delsemme and Miller 1971; $p(T)$ is the vapor pressure in thermodynamical equilibrium fitted by Busch (1960), μ the mass of one molecule and k the Boltzmann constant), $L(T) = -582 \cdot T + 2.62 \cdot 10^6$ the latent heat of sublimation in $\mathrm{J\,kg^{-1}}$ which was obtained by fitted data (Auer 1961) and $-F_{\mathrm{s}}$ the net heat conduction flux towards the interior of the nucleus. With an initial temperature distribution in the nucleus (the nucleus is assumed to be at its radiative equilibrium temperature far from the sun) and the initial heliocentric distance, this equation provides F_{s}.

The surface temperature depends on the heat conduction process in the interior of the nucleus. In order to simulate this process, the nucleus is divided into l radial layers of equal volume (see Fig. 1; temperatures are cell-centered while heat fluxes are defined at cell edges). The heat flux F_i between the layers i and $i+1$ is calculated from

$$F_i = -K(T(R_i)) \cdot \frac{T_{i+1/2} - T_{i-1/2}}{\Delta r_i}.$$

Here $T(R_i)$ is the temperature interpolated at the position R_i corresponding to F_i, Δr_i the distance between the positions of $T_{i-1/2}$ and $T_{i+1/2}$, and $K(T)$ the heat conductivity of the ice in $\mathrm{W\,K^{-1}\,m^{-1}}$. The heat conductivity is not very well known for cometary ice and is one of the variables in the model. The temperature at the layer boundaries and the Δr_i are calculated by linear interpolation:

$$T(R_i) = T_{i-1/2} + \frac{T_{i+1/2} - T_{i-1/2}}{R_{i+1} - R_{i-1}} \cdot (R_i - R_{i-1})$$

and

$$\Delta r_i = \frac{1}{2} \cdot (R_{i+1} - R_{i-1})\,.$$

The upper boundary flux F_l is equal to F_{s}, the lower $F_0 = 0$ because of radial symmetry. The heat fluxes allow to simulate the heat diffusion process by calculating the time derivative of the temperature in each layer, obtained from energy conservation:

$$\dot{T}_{i-1/2} = \frac{-4\pi R_i^2 \cdot F_i + 4\pi R_{i-1}^2 \cdot F_{i-1}}{V_i \cdot \varrho \cdot C_p(T_{i-1/2})}$$

with V_i the volume of layer i and $C_p(T) = 16.1 \cdot T^{0.871} - 39.2$ the heat capacity of ice in $\mathrm{J\,kg^{-1}\,K^{-1}}$ obtained from a fit to data (Hobbs 1974, Auer 1961).

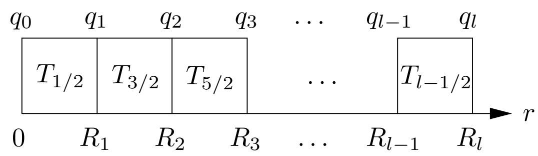

Figure 1: Layer geometry

Connecting this with an orbit integrating routine, the model provides among other quantities the nucleus size R, the sublimation rate $\dot{m} \equiv -Z \cdot 4\pi R^2$, and the radial temperature profile of the nucleus as a function of time or true anomaly.

3 Model test: $\dot{m}$ of comet P/Halley

As a model test we calculate the mass of water ice sublimating from the surface of comet P/Halley. The only free parameter in the model test is the thermal conductivity of the cometary material.

The nucleus of comet P/Halley has approximately the shape of a prolate ellipsoid with semi-axes [km] $8 \times 4 \times 4$ (Whipple 1987). A sphere with the same surface has a radius R_0 of $\approx 5000\,\mathrm{m}$. Measurements during the Giotto mission showed that $A \approx 0.04$. We assume a density of ϱ =931 kg m^{-3} (the density of crystalline ice at 150 K). Some of our sungrazer models will use a lower density of 600 kg m^{-3}. However, we perform our model tests for a single density only because the sublimating mass $\dot{m} \equiv -Z(T_S) \cdot 4\pi R^2$ does not depend strongly on density. Although the change in surface temperature with time and therefore Z varies somewhat with ϱ, the effect is much weaker than the dependence of temperature on heat conductivity. Since the total mass sublimated during one orbital period is given by $m \approx 4\pi R_0^2\,\Delta R\,\varrho$, independence of the sublimated mass on ϱ means that ΔR, the radius of the layer which is sublimated during one orbit, is approximately proportional to $1/\varrho$.

In Fig. 2 we show the results of our model using the parameters discussed above. The orbit of comet P/Halley is shown in the form of curves for $\dot{m}$ as functions of the true anomaly ϑ. We varied the heat conductivity between 0 and the values for crystalline ice (taken from Hobbs (1974) and Bosnjakovic (1972) and shown in Fig. 3 as a function of temperature). The model results are compared to actual measurements. The theoretical curves fit through the measurements, which themselves scatter by up to half an order of magnitude. The three empty circles at $\vartheta = 0$ are peaks of the model curves (with one free parameter $n = 0, 1, 2$) as derived by Peale (1989) from the lightcurve of P/Halley scaled with the sublimation rate at spacecraft encounter.

Some discrepancies between model and observations exist. The model predicts the production rate at perihelion to be higher than the observed values. This can be readily explained by P/Halley not consisting of water ice only and by the observation that only $\approx 10\,\%$ of Halley's surface is active (Keller et al. 1987). Also the increase of the production rate is too steep in the model, i.e. the onset of sublimation of water ice is too close to the sun.

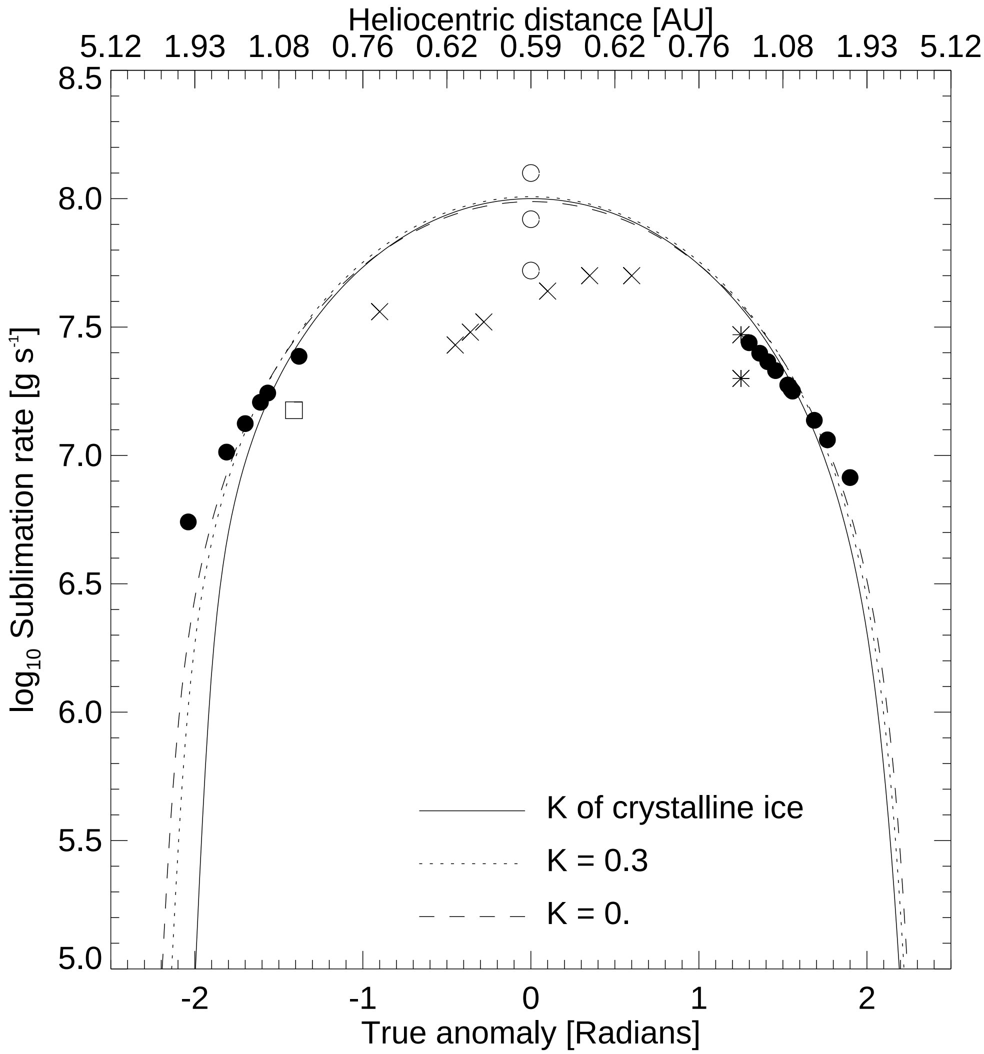

Figure 2: Comparison of the sublimation rate of comet P/Halley between our model calculations for various heat conductivities and several measurements. The model radius of the comet is 5000 m. The temperature dependent heat conductivity of crystalline ice was taken from Bosnjakovic (1972) and Hobbs (1974). Measurements:
$\star$: in situ estimates at Giotto fly-by from Krankowski and Moroz (Peale 1989); $\times$: estimates from Ly α intensities measured by the Pioneer Venus spacecraft, Stewart 1987 (Peale 1989); empty circles at $\vartheta = 0$: peaks of the model curves ($n = 0, 1, 2$) calibrated by the sublimation rate at spacecraft encounter (Peale 1989); solid circles: Gas mass release rate (Singh 1992); $\square$: Swamy 1990

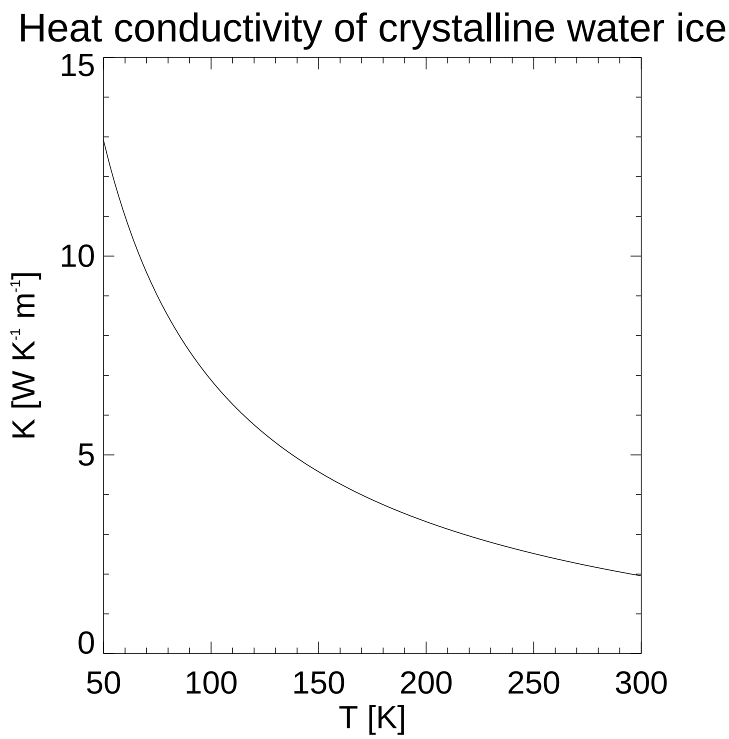

Figure 3: Heat conductivity of crystalline ice as a function of temperature. After Hobbs (1974) and Bosnjakovic (1972).

This discrepancy decreases with decreasing thermal conductivity indicating that the thermal conductivity of cometary water ice is much smaller than that of crystalline ice. A similar conclusion was drawn by Weissman (1987) and Julian et al (2000). On the other hand, the dependence of the total sublimation on the thermal conductivity is very weak. ΔR only varies between 1.79 m and 1.92 m in the 3 cases shown in fig. 2.

Model tests for comet C/Hale-Bopp 1995 O1 show additional evidence for a low thermal conductivity. The lower the thermal conductivity the earlier is the onset of significant sublimation. This result is in agreement with Kührt (1999) who was able to explain the early onset of sublimation of Hale-Bopp with a combination of a low thermal conductivity and the low inclination of the cometary spin axis relative to its orbital plane.

Although the model does not reproduce all aspects of the observations and the comparison is hampered by the large scatter of the measurements, we conclude that the simple model is a good first approximation, despite its limitations of assuming a spherical nucleus of pure H_2O ice.

4 Destruction by sublimation alone

In this section, we calculate the maximum size of a comet destroyed by sublimation alone as a function of the parameters ϱ, q and A which describe the comet in our one dimensional model. Other disruption mechanisms will be discussed in later sections.

4.1 Thickness of the sublimating surface layer of a sungrazer

We now use our model to calculate the thickness of the layer which will sublimate during the perihelion passage of a sungrazer. We will consider crystalline and porous water ice.

The thickness of the sublimated layer does not depend significantly on the radius of the comet. This can be seen from

$$\frac{dm}{dt} = 4\pi R^2 \varrho \, \frac{dR}{dt} = Z \, 4\pi R^2 \tag{2}$$

or

$$\frac{dR}{dt} = \frac{Z}{\varrho}, \tag{3}$$

where $\frac{dm}{dt}$ is the sublimation rate, Z the sublimation flux, and R the radius of the cometary nucleus. The sublimation flux and therefore the change in radius do not depend explicitly on the size of the nucleus. There is a small implicit dependence: A very small nucleus may be heated up internally very rapidly and then heat conduction cannot transport energy inward from the surface as efficiently as for a larger nucleus. Since our model as well as previous sublimation models (e.g. Weissman 1983, Kührt 1999) show that comets are heated up to a depth of at most a few meters, this effect can be neglected for all practical purposes.

Fig. 4 shows the thickness of the sublimated layer for a sungrazer consisting of compact water ice (ϱ =931 kg/m^3 and heat conductivity of crystalline ice as shown in fig. 3) as a function of heliocentric distance. The sublimation during a complete orbit is considered. The upper size limit derived this way is too high. The disappearance of the comets implies that they do not reach a heliocentric distance of more than a few solar radii post perihelion. However, the difference is not very large. For a typical sungrazer, only 20–25 % of the radius of the sublimated layer evaporates post perihelion at a heliocentric distance of more than 3 solar radii. Since the maximum heliocentric distance a sungrazer can reach after perihelion without being discovered is hard to define, we conservatively define our upper size limits as the layer which evaporates during one full orbit.

A comparison of fig. 4 with the results of the similar model of Weissman (1983) shows a maximum difference of $\approx 7\,\%$. While this shows the excellent agreement between the two models, it is not an estimate of the error of the models, because both use the assumption of a spherical nucleus composed of pure water ice.

The cometary H_2O ice may be porous and not crystalline which affects two quantities in the model: heat conductivity K and density ϱ. Heat conductivity is expected to be much lower in porous ice than in crystalline ice. Fig. 5 shows results of our model for various values of K. The variation of the thickness of the sublimated layer with K is less than 3 %.

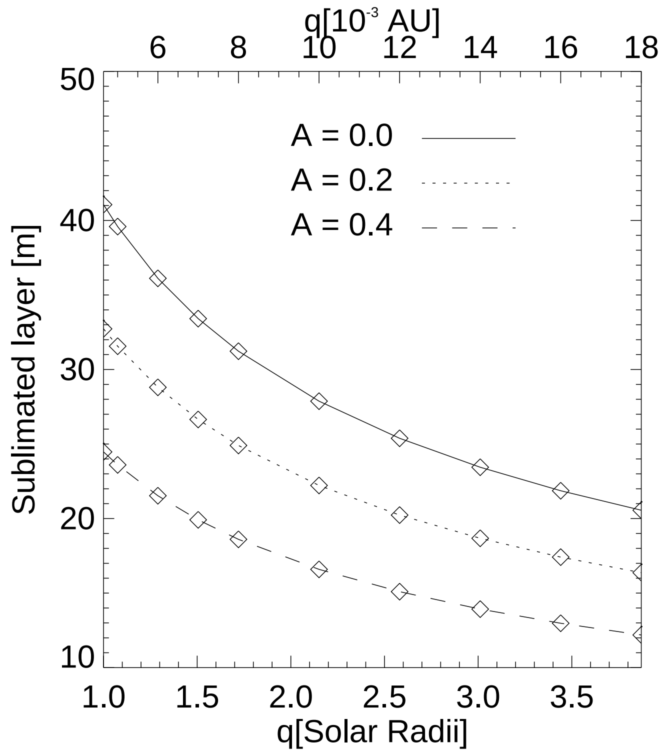

Figure 4: Thickness ΔR of the layer sublimated from a sungrazing nucleus of compact H_2O ice during the complete perihelion passage.

Therefore the choice of K is uncritical as long as one is interested in the total sublimated mass only. In the model we use $K = 0.15$ W/(K m).

The density of porous ice is also lower than that of crystalline ice. Here we use the density of 600 kg/m^3 which Asphaug and Benz (1996) derived for comet D/Shoemaker-Levy 9.

Fig. 6 shows the thickness of the sublimated layer for a comet which consists of porous ice. The values are about 50 % higher than for the comet made of crystalline ice and the maximum radius is about 60 m.

4.2 Semi-analytical approximation

Comparing the radiation and the sublimation terms in Eq. 1 (Fig. 7) shows that whenever the sublimation process becomes important, it is orders of magnitude higher than the radiation. If one is interested in the destruction of sungrazers by sublimation, therefore mainly in the quantity $\dot{m}$, the radiation can be neglected.

Model calculations with sungrazers showed that at small heliocentric distances ≈ 85 % of the solar radiation energy goes into sublimation (Fig. 8). Since only a negligible part of the sublimation takes place at large heliocentric distances where sublimation is low and thermal

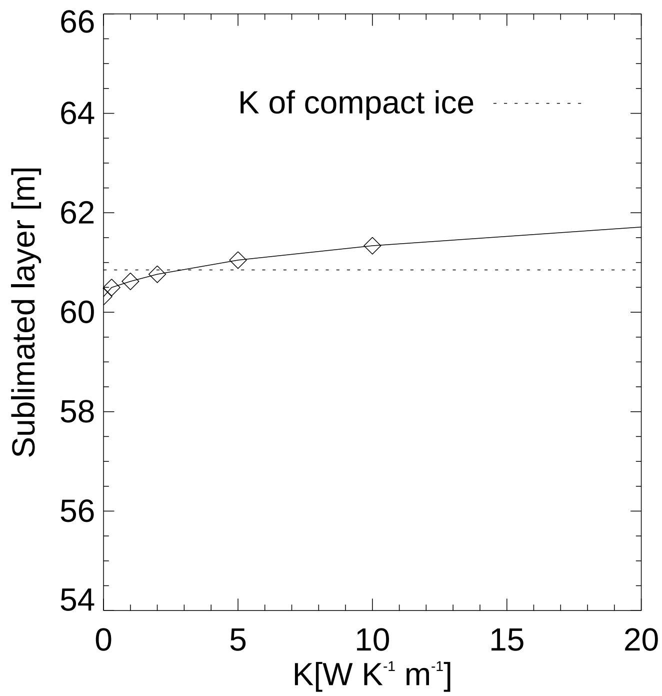

Figure 5: Layer sublimated from a sungrazer during one perihelion passage as a function of the heat conductivity. The density is $600\,\mathrm{kg\,m^{-3}}$, the initial radius of the comet $200\,\mathrm{m}$, and the heliocentric distance at perihelion $0.005\,\mathrm{AU}$ ($1.1\,\mathrm{R_{sun}}$).

radiation becomes important, we can simplify Eq. 1 to

$$\frac{P_{\text{sun}}(1-A)}{16\pi d^2} \cdot 0.85 = Z \cdot L \tag{4}$$

For H_2O, the latent heat is nearly independent of the temperature, allowing to consider L as a constant. Replacing Z by $-\dot{m}/(4\pi R^2)$ and solving for $\dot{m}$ yields

$$\dot{m} = -\frac{P_{\text{sun}} \cdot (1-A)}{4L \cdot d^2} \cdot R^2 \cdot 0.85 \tag{5}$$

If $\dot{m}$ is substituted with $4\pi\varrho R^2 \cdot \dot{R}$, then solving for $\dot{R}$ yields:

$$\dot{R} = -\frac{P_{\text{sun}} \cdot (1-A)}{16\pi\varrho L \cdot d^2} \cdot 0.85 \tag{6}$$

For parabolic sungrazer orbits, the time derivative of the true anomaly is $\dot{\vartheta} = \sqrt{2GM_{\text{sun}}q}/d^2$ with G the gravitational constant and $M_{\text{sun}} \approx 1.989 \cdot 10^{30}\,\mathrm{kg}$ the solar mass. Dividing Eq. 6 by $\dot{\vartheta}$ yields

$$\frac{dR}{d\vartheta} = -\frac{P_{\text{sun}} \cdot 0.85}{16\pi \cdot \sqrt{2GM_{\text{sun}}}} \cdot \frac{1-A}{\varrho L\sqrt{q}} \tag{7}$$

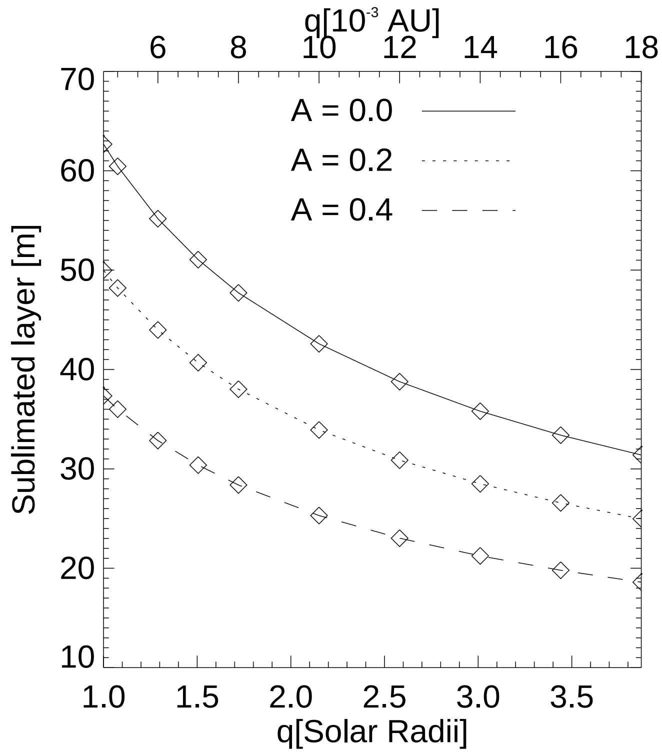

Figure 6: Thickness ΔR of the layer sublimated from a sungrazing nucleus of porous H_2O ice (density $600\,\mathrm{kg\,m^{-3}}$, heat conductivity $0.15\ \mathrm{K\,W^{-1}\,m^{-1}}$) during the complete perihelion passage

The rate of change in radius is independent of the position on the orbit. This is a consequence of the sublimated energy being a constant fraction of the solar input and is valid only when large heliocentric distances are not important. Integration of eq. 7 over the entire orbit yields the thickness $\Delta R := |\int_{-\pi}^{+\pi} \frac{dR}{d\vartheta} d\vartheta|$ of the sublimated layer:

$$\boxed{\Delta R = \frac{P_{\mathrm{sun}} \cdot 0.85}{8 \cdot \sqrt{2GM_{\mathrm{sun}}}} \cdot \frac{1-A}{\varrho L \sqrt{q}}} \tag{8}$$

It is important to note that ΔR is independent of R_0. Collecting all comet-independent numerical factors and fixing $L \approx 2.5 \cdot 10^6\,\mathrm{J\,kg^{-1}}$ yields

$$\Delta R \approx 10^9 \cdot \frac{1-A}{\varrho\sqrt{q}}, \tag{9}$$

where ΔR and q are in meters and ϱ in $\mathrm{kg/m^3}$. A similar result was obtained by Huebner (1967).

The comparison of the results of the numerical model with Eq. 8 shows a maximum discrepancy of 4 %. Within the accuracy of the model, Eq. 8 can clearly be used to calculate ΔR. The advantage of the analytical approximation for future applications is that Eq. 8 is much easier to use than the full numerical model.

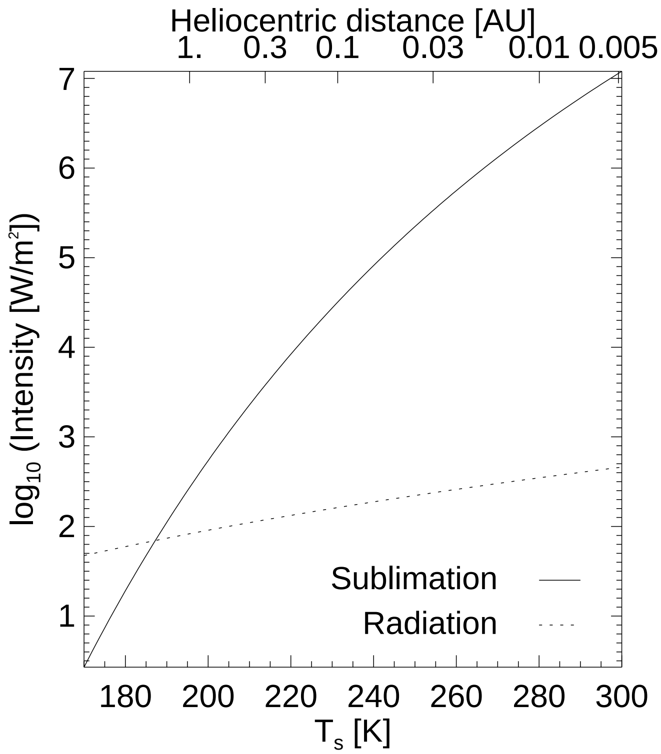

Figure 7: Comparison of the radiation and the sublimation terms as functions of the surface temperature. The upper axis denotes the heliocentric distance of a sungrazer with perihelion at 0.005 AU.

4.3 Discussion

Given that we assumed that a sungrazer is destroyed by sublimation alone, its initial radius R_0 cannot exceed ΔR. Hence Eq. 8 allows to calculate maximum initial sizes as a function of ϱ. q is known for a given sungrazer, and A can be set to zero as generally the cometary albedo is very low, resulting in an upper size limit valid for any albedo.

Considering only sungrazers but no sun-impactors implies $q \geq R_{\mathrm{sun}}$ (solar radius, $\approx 6.96 \cdot 10^8\,\mathrm{m}$); Inserting $A = 0$ and $q = R_{\mathrm{sun}}$ in eq. 9 yields an upper size limit for all sungrazers with a given density:

$$R_0 \leq 3.8 \cdot 10^4 \cdot \varrho^{-1},$$

where ϱ is in $\mathrm{kg\,m^{-3}}$ and R_0 in m. For the density of porous ice, $\approx 600\,\mathrm{kg\,m^{-3}}$, which was derived for comet Shoemaker-Levy 9 in Asphaug and Benz (1996), the upper limit in size for the comets is $\approx 63\,\mathrm{m}$.

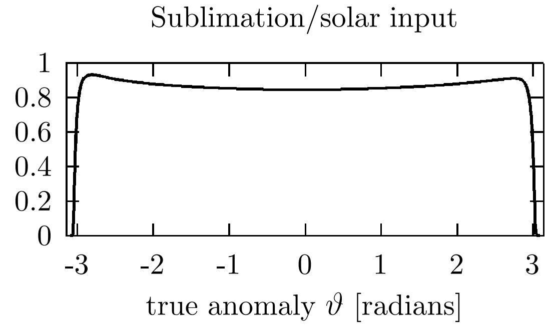

Figure 8: Ratio of the energy lead into sublimation to the total solar radiation energy

5 Additional destruction mechanisms

If sungrazers are larger than the above size limit for complete destruction by sublimation alone ($R_0 > \Delta R$), then an additional mechanism is needed to explain the disappearance of all SOHO sungrazers. Since the lifetime against disruption of comets in general is much larger than one perihelion passage, we restrict possible disruption mechanisms to effects that are expected to increase with decreasing heliocentric distance.

Since most of the sungrazers are likely to pass within the Roche limit of the sun (Asphaug and Benz (1996) give $R_{\mathrm{Roche}} = 1.51 \cdot \sqrt[3]{M_{\mathrm{sun}}/\varrho} = 3.23 R_{\mathrm{sun}}$ for $\varrho = 600\,\mathrm{kg\,m^{-3}}$), tidal breakup is an obvious candidate mechanism. We show in the next subsection that the combination of sublimation and tidal breakup increases the upper size limits derived for destruction by sublimation alone if and only if sublimation is highly anisotropic.

A second mechanism which may favor very low heliocentric distances is disruption by thermal stress. The second subsection shows that thermal stress may separate small pieces from the comet but will be insufficient to completely disrupt a large body.

5.1 The combination of sublimation and tidal breakup

In this subsection we first discuss the isotropy of the sublimation from the cometary nucleus. Since with the existing data it is difficult to evaluate to what extent sublimation from sungrazers is non-isotropic, we then treat tidal disruption for the two extreme cases of isotropic sublimation and completely non-isotropic sublimation (no activity on the nightside of the comet). We show that for all realistic cometary densities the combination of isotropic sublimation and tidal breakup is insufficient to destroy a comet larger than ΔR during one perihelion passage. We calculate upper size limits for the combination of sublimation and tidal disruption in the case of completely non-isotropic sublimation.

5.1.1 Isotropy of sublimation from a cometary nucleus close to the sun

Isotropy of sublimation is an important parameter in the treatment of tidal breakup. In case of isotropic sublimation, the reaction force of the sublimating molecules on the comet causes a compression which acts against tidal stress and may prevent a comet from tidal disruption.

While sublimation is a surface effect, the resulting compression is felt throughout the body. The response time of the comet to an increase in surface pressure is of the order $\tau = R/c_s$, where R is the radius of the cometary nucleus and c_s the speed of sound in water ice. For compact water ice, $c_s = \sqrt{E/\varrho}$, where E is the Young modulus of the ice and ϱ its density. For $E \approx 10^{10}$ Pa (Hobbs 1974) and $\varrho = 1000\,\mathrm{kg\ m^{-3}}$, the sound speed is about $3\,\mathrm{km/s}$, resulting in a response time of $0.3\,\mathrm{s}$ for $R = 1\,\mathrm{km}$. For porous ice, the propagation of pressure is more complicated, but sound speeds of the same order of magnitude as for compact water ice have been measured for materials which are used as cometary analogs in simulation experiments (Kohl et al. 1990). Therefore the propagation of the compression through the nucleus of the comet is fast compared to changes in sublimation flux. In case of completely non-isotropic sublimation, there is no sublimation from the night-side of the nucleus and therefore no compression. The reaction force from molecules sublimating on the dayside acts as the well known non-gravitational force which in this case pushes the comet away from the sun.

In our model sublimation is isotropic as a consequence of the fast rotator approximation, i.e. the assumption that the cometary rotation is fast compared to the time scale of changes in the solar input flux. Close to perihelion the modeled sublimation rate of a sungrazer changes by an order of magnitude within 2–3 hours. Typical rotation rates of comets are between 5 and 20 hours (Jewitt 1992). Although sungrazing comets may rotate faster than other comets because they could have gained rotational energy in there history of multiple tidal disruptions from a common progenitor, it is possible that the fast rotator approximation is invalid close to perihelion.

If the cometary rotation is slow compared to changes in solar input, sublimation will be highly non-isotropic unless the coma of the comet is optically thick. Salo (1988) has used a Monte-Carlo model of scattering in the coma of a comet to calculate the spatial distribution of the incoming sunlight on a comet as a function of the optical depth of the coma. We now try to estimate the optical depth of the coma of a sungrazer close to perihelion in order to evaluate if significant sublimation from the night side will take place.

The optical depth τ can be written as:

$$\tau = \int_{s_{min}}^{s_{max}} N(s)\sigma_c(s)ds \tag{10}$$

Here $N(s)$ is the column density of particles with a size between s and $s + ds$ and $\sigma_c(s)$ their scattering cross section. $s_{\min}$ and $s_{\max}$ are the minimum and maximum grain size, respectively. For simplicity, we assume that the outflow of the dust particles is isotropic and with constant velocity, and that their size distribution is independent of the distance from the nucleus. Then the column density is

$$N(s) = \int_R^\infty f(s)\frac{R^2}{r^2}dr = R\,f(s) \tag{11}$$

where $f(s)$ is the number density at the cometary surface of particles with a radius between s and $s + ds$, and R the radius of the nucleus.

The scattering cross section is approximated by Rayleigh scattering for small particles ($< 600\,\mathrm{nm}$) and taken as the geometric cross section of the particle for larger particles:

$$\sigma_c(s) = \begin{cases} \pi s^2 & (s > s_f = 600\,nm) \\ \pi \frac{s^6}{s_f^4} & (s < s_f = 600\,nm) \end{cases} \tag{12}$$

We take the particle size distribution $f(s)$ from *in situ* measurements in the coma of comet P/Halley (Mazets et al. 1986):

$$f(s) = \begin{cases} c_1 s^{-2} & (s < s_0 = 600\,nm) \\ c_2 s^{-2.75} & (s_0 < s < s_1 = 6000\,nm) \\ c_3 s^{-3.4} & (s > s_1) \end{cases} \tag{13}$$

Three conditions are needed to determine the three constants c_1, c_2, and c_3. Two of these conditions are that eq. 13 is continuous at s_0 and s_1. The third condition is that the mass of all dust particles on the surface as expressed by $f(s)$ must be equal to that described by the ratio between sublimation flux and velocity:

$$\int_{s_{\min}}^{s_{\max}} f(s) \frac{4}{3} \pi s^3 \varrho \, ds = \frac{Z_d}{v} \tag{14}$$

Here ϱ is the density of the dust particles, Z_d the dust production rate, and v the outflow velocity of the dust particles.

Now eq. 10 can be solved easily using eqs. 11–14. We consider 2 cases: Comet P/Halley at perihelion and a sungrazing comet with a radius of 100 m. In both cases we have taken the parameters $\varrho = 1000\,\mathrm{kg\,m^{-3}}$ (we assume the dust to be somewhat denser than the comet in general), $s_{\min} = 0$ (a choice of little importance because the contribution of small Rayleigh scatterers to the total optical depth is very small), and $s_{\max} = 1\,\mathrm{mm}$. It should be noted that $s_{\max}$ is the maximum particle size of the *visible* dust because determination of the production rate of the dust Z_d from the sublimation model requires knowledge of the dust/gas-ratio. This ratio is determined either from remote observations which are not sensitive to dust particles which are much larger than the wavelength of the observations or by *in situ* measurements which register particles smaller than a mm only. There might be an additional component of unobserved large dust particles which cannot be included in our estimate. We assumed that half of the production rate in our model is gas production and the other half is dust which is carried away by the gas, corresponding to a typical cometary dust/gas ratio of 1.

For comet P/Halley we use a radius of 5000 m, an outflow velocity of 500 m/s, and a dust production rate of $1.5 \times 10^{-4}\ \mathrm{kg\,m^{-2}\,s^{-1}}$, corresponding to half the total mass loss at perihelion as derived in section 3. The resulting optical depth is $\tau = 0.02$, somewhat lower than estimates of the global optical depth on comet Halley (0.05, Thomas and Keller (1990)), but of the same order of magnitude.

For the sungrazer, we assume that the radius is 100 m, the outflow velocity 1000 m/s, and a dust production rate of $0.5\,\mathrm{kg\,m^{-2}\,s^{-1}}$, which again is half the sublimation rate as calculated for a typical sungrazer close to perihelion. The resulting optical depth is 0.7. From fig. 3–5 in Salo (1988) we estimate the minimum night side flux at $\tau = 0.7$ to be about 10 % of the maximum day side flux.

While the absolute values of τ are highly uncertain because of the uncertainties in some of the parameters we used (e.g. $s_{\max}$, $f(s)$) and because of our simplifying assumptions (especially isotropic dust production and negligence of dust evaporation and fractionation), it seems remarkable that the optical depth in the coma of a comparatively small sungrazing comet may be more than an order of magnitude larger relative to that in the coma of a large comet at moderate heliocentric distance. The reason is that the difference in production rate at perihelion, which is more than 3 orders of magnitude higher for the sungrazer than for Halley, more than outweighs the effect of the difference in size.

Because of the large uncertainty in the absolute value of τ it is difficult to establish firm limits on the non-isotropy of the sublimation of a sungrazing comet close to perihelion. Therefore we will now consider the destruction of sungrazers by a combination of sublimation and tidal disruption for the two extreme cases of isotropic sublimation and of no sublimation pressure at the nightside of the comet.

5.1.2 Tidal breakup in case of isotropic sublimation

Most favorable for tidal breakup is the assumption of a comet without tensile strength: a rubble pile. Such a model has indeed been suggested for comets (e.g. Weissman 1986). In this case, the only processes working against tidal disruption are the self-gravity of the comet and the sublimation pressure. For $\varrho = 600\,\mathrm{kg\,m^{-3}}$ and $R = 200$ m, the strength due to self-gravity, $G\varrho^2R^2$ (Sridhar and Tremaine 1991), is about 1 Pa. For comparison, the isotropic sublimation pressure in our model is $|\dot{m}| \cdot v/(4\pi R^2) = Z \cdot v$ with v the thermal velocity of the sublimated molecules. For temperatures around perihelion ($T \approx 280$ K), Z is about 1 kg per m^2 and s, and $v \approx \sqrt{8kT/\pi\mu}$, is about $600\,\mathrm{m\,s^{-1}}$. This corresponds to a sublimation pressure of 600 Pa, which is much larger than self-gravity.

Neglecting self-gravity, the tidal stress σ_T must exceed the sublimation pressure of 600 Pa in order to be sufficient to disrupt the comet. The tidal stress is given by $\sigma_T(d) = GM_{\mathrm{sun}}\varrho R^2/d^3$ (Asphaug and Benz 1996), so that it reaches its maximum value for $d = R_{\mathrm{sun}}$. We define the critical radius of the nucleus R_{crit} as the radius for which tidal stress is just sufficient to disrupt the comet:

$$R_{crit} = \sqrt{\frac{600 \cdot R_{\mathrm{sun}}^3}{GM_{\mathrm{sun}}\varrho}} = 3.9 \cdot 10^4 \cdot \varrho^{-\frac{1}{2}}, \tag{15}$$

where ϱ is in $\mathrm{kg\,m^{-3}}$ and R_{crit} in m. If the nucleus is smaller than R_{crit}, tidal stress is too weak to destroy the comet against the compressive force of sublimation pressure. R_{crit} is very large compared to ΔR, therefore the decrease of the cometary radius by sublimation of the surface layer on the comet's way to perihelion can be neglected here.

We now show that a comet with radius $> R_{crit}$ cannot break up in boulders which are sufficiently small to be sublimated completely. In order to destroy the comet completely by sublimation and tidal breakup, the largest remnant after the disruption must be smaller than ΔR. Hence the ratio f of the mass of the largest remnant to the mass of the nucleus before the breakup is limited by

$$f < \left(\frac{\Delta R}{R_{crit}} \right)^3 \tag{16}$$

ΔR is given by Eq. 9 and limited by

$$\Delta R \leq 10^9 \cdot \frac{1}{\varrho \sqrt{R_{\text{sun}}}} = 3.8 \cdot 10^4 \cdot \varrho^{-1} \tag{17}$$

Substituting R_{crit} and ΔR to Eq. 16 from Eqs. 15 and 17 yields

$$f \leq 0.915 \cdot \varrho^{-\frac{3}{2}} \tag{18}$$

In Asphaug and Benz 1996, the "normalized periapse" $b := q/R_{\text{Roche}}$ necessary for a tidal disruption of a rubble pile with largest remnant mass fraction f, is given as a function of f:

$$b(f) \approx \frac{1}{9} + \frac{3}{5} \cdot \sqrt{f} + \frac{1}{6} \cdot \left(f^{12} - f^3 \right) \tag{19}$$

From the monotonous increase of $b(f)$ follows that the upper limit Eq. 18 for f implies an upper limit for b:

$$b \leq b(0.915 \cdot \varrho^{-\frac{3}{2}})$$

This yields an upper limit for $q = b \cdot R_{\text{Roche}}$. On the other hand, we have the restriction $q \geq R_{\text{sun}}$:

$$R_{\text{sun}} \leq q = b \cdot R_{\text{Roche}} \leq b(0.915 \cdot \varrho^{-\frac{3}{2}}) \cdot 1.51 \cdot \sqrt[3]{M_{\text{sun}}/\varrho} \tag{20}$$

Solving Eq. 20 numerically for ϱ results in

$$\varrho \leq 55 \, \frac{\text{kg}}{\text{m}^3}$$

This value is probably much lower than the density of cometary nuclei, although there are very few determinations of densities of comets. After the fly-bys of five spacecraft at comet P/Halley several attempts were made to determine the density of the comet (Rickman 1986, Rickman 1989, Sagdeev et al. 1988). The results were contradictory, probably because uncertainties in the mass determination were so high that no significant constraints on the density of P/Halley could be made (Peale 1989). The only reliable density estimates of a comet were derived from the breakup of comet Shoemaker-Levy 9 and result in approximately 600 kg m^{-3} (e.g. Asphaug and Benz 1996). Since this is more than an order of magnitude above our upper limit, we conclude that in the case of isotropic sublimation a sungrazer larger than the size limit for destruction by sublimation alone cannot be destroyed completely by a combination of sublimation and tidal breakup.

5.1.3 Tidal breakup in case of completely non-isotropic sublimation

We first note that non-isotropic sublimation has no major consequences on the thickness of the sublimated layer derived in section 4: We showed that the energy balance close to the sun is dominated by solar input and sublimation. Since the solar input is independent on the rotation rate of the comet, conservation of energy requires that the sublimation rate will not be seriously affected by non-isotropic sublimation.

For the treatment of tidal breakup the difference between isotropic and non-isotropic sublimation is the absence of sublimation pressure in the latter case. Only self gravity and the tensile strength of the comet (if present) work against disruption by tidal stress. This case is in many respects similar to the situation which led to the disruption of comet Shoemaker-Levy 9 during its close approach to Jupiter. The perihelion distance of the average sungrazer in solar radii (1.31 R_{sun}) is very close to the perijove distance of Shoemaker-Levy 9 to Jupiter in Jovian radii. Therefore some of the results about the splitting of comet Shoemaker-Levy 9 are valid for the analysis of the disruption of sungrazing comets in absence of sublimation pressure at the night side.

In order to derive upper size limits for a comet which can be completely destroyed by a combination of tidal disruption and sublimation, we again assume a body without tensile strength. We use the results from Asphaug and Benz (1996) (reproduced as eqs. 19 and 16 in the previous subsection) to determine the maximum size of a strengthless comet which may disrupt in a way that all fragments are smaller than the largest fragment size which will sublimate completely. Fig. 9 shows the results. If we assume (somewhat arbitrarily) that the minimum conceivable density of a comet is 200 kg m^{-3}, the maximum size before disruption would be about 360 m.

Finally, in case of non-isotropic sublimation it is possible that variations in sublimation pressure may induce a stress on the comet. The difference between the pressure at the day side and at the night side is of low importance here as it acts on the comet as a whole. On the other hand, local differences in sublimation pressure may act to separate fragments from a non-spherical nucleus (the reaction force may act on material close to the visual limb as seen from the sun). For most shapes of the nucleus such local pressure gradients result in the separation of small fragments only. Therefore they are unlikely to increase our upper size limits significantly. A more quantitative treatment of local pressure effects and their influence on the size of the sublimating layer would require a full 3-dimensional model of the cometary nucleus which is beyond the scope of the present paper.

5.1.4 Summary

The rapid perihelion passage of sungrazing comets may cause non-isotropic sublimation, although the unknown rotation rates of the sungrazers and the uncertain optical depth of their coma make it difficult to estimate the difference between the sublimation fluxes at the dayside and at the nightside. Should sublimation be isotropic, a combination of tidal disruption and sublimation will not destroy a comet which is larger than the size limits derived from destruction by sublimation alone. In case of completely non-isotropic sublimation, the size and density limits are modified as shown in Fig. 9.

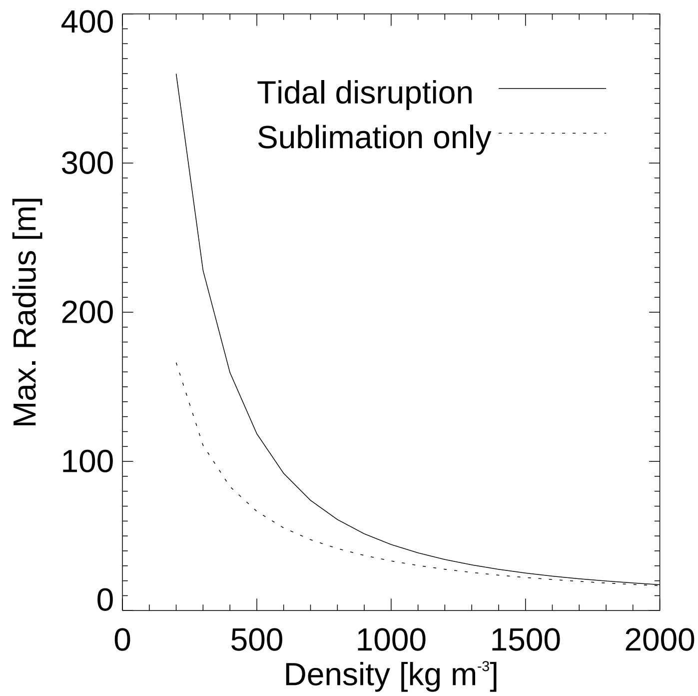

Figure 9: Maximum radius of a comet which will be destroyed by sublimation alone (dashed line) and by a combination of sublimation and tidal disruption (solid line). No tensile strength of the comet and no sublimation on the nightside is assumed.

5.2 Disruption by thermal stress

Thermal stresses in comets are generally much larger than tidal forces, even for close encounters between a comet and the sun. Shestakova and Tambovtseva (1997) note that even in Comet D/Shoemaker-Levy 9 during Perijove in 1992 thermal stress close to the surface exceeded the tidal forces on the comet by 4 or 5 orders of magnitude. Therefore thermal breakup needs to be considered as another possible destruction mechanism for sungrazing comets.

The thermal stress on the surface layer of a comet introduced by non-linear radial temperature variations $T(r)$ can reach several MPa close to the surface of a comet on the orbit of P/Halley (Kührt 1984, Tauber and Kührt 1987). This value can increase to several hundred MPa if there are inclusions of a material with a different thermal expansion coefficient in a background material (e.g. CO or CO_2 inclusions in H_2O ice) and may be still higher when the sublimation temperature of the included material is exceeded.

Thermal stress within the H_2O ice cannot completely disrupt a sungrazing comet. The main difference between the thermal profile of a sungrazer at perihelion and that of a comet at 1 AU is the higher surface temperature of the sungrazer (in our case of pure H_2O ice about 300 K versus 200 K, see Fig. 10). Because of the high surface temperature nearly all of the energy input goes into sublimation of the ice. This leads to a very steep temperature

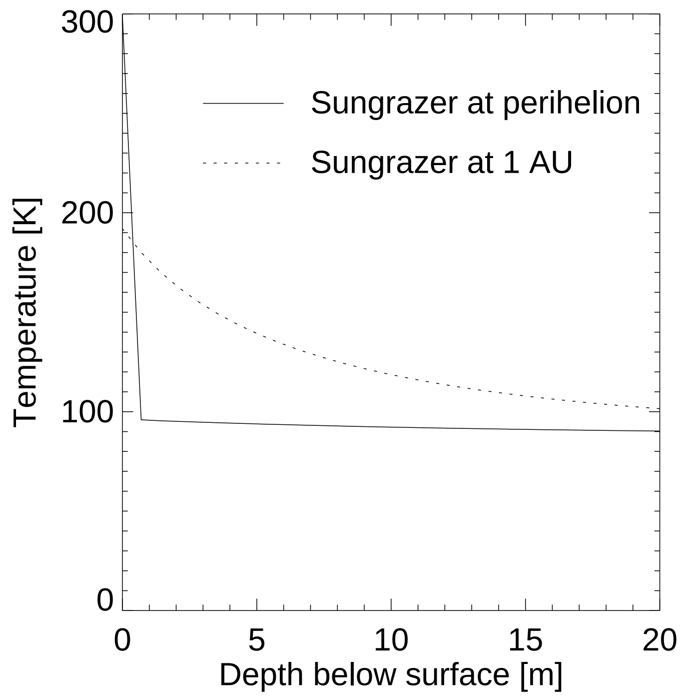

Figure 10: Temperature profile of a sungrazer at perihelion and at 1 AU. A perihelion distance of 0.005 AU (1.1 R_{sun} and the conductivity of crystalline ice was used.

gradient immediately below the surface. Below surface depth of tens of centimeters, the temperature gradient is smaller close to the sun than it is at 1 AU. Therefore the thermal stress in a sungrazer does not increase during perihelion passage except for a very small layer below the surface. Since the hot surface material sublimates rapidly, there is no significant effect of thermal stress within the H_2O ice on the destruction of the comet.

Inclusions of e.g. CO or CO_2 in the H_2O ice may cause increased thermal stress. Cracks in the ice may be induced and a block of cometary material may be separated from the nucleus and accelerated by the gas escaping from the inclusion. Tauber and Kührt (1987) solve the rocket equation to calculate the maximum mass m_f of a separated fragment which reaches escape velocity from the cometary nucleus:

$$m_f = m_i \frac{\exp\left(\frac{v_e+g_0 t}{v}\right)}{\exp\left(\frac{v_e+g_0 t}{v}\right) - 1} \tag{21}$$

Here m_i is the mass of the inclusion, v_e the escape velocity from the cometary nucleus, v the velocity of the escaping gas, g_0 the gravitational acceleration at the surface of the comet, and t the time needed for complete sublimation of the inclusion. Since v increases and t decreases as a comet approaches the sun, the maximum fragment mass increases strongly during the perihelion passage of a sungrazing comet.

From a comparison with minor fragments of observed cometary splittings, Tauber and Kührt (1987) estimate a typical radius of an inclusion of $r_i = 0.5$m. The sublimation time is determined from the mass loss of the inclusion:

$$\frac{dm}{dt} = \frac{4}{3}\pi\varrho\,\frac{dr^3}{dt} = 4\pi r^2\varrho\,\frac{dr}{dt} = Z\,4\pi r^2 \tag{22}$$

Integration yields:

$$t = \frac{r_i\varrho}{Z} \tag{23}$$

For a spherical inclusion with $r_i = 0.5$m, $\varrho = 600$ kg/m^3, and $Z = 3$ kg/s (the model value for H_2O on a typical sungrazer at perihelion; higher values are expected for inclusions of CO or CO_2), the sublimation time is 100s. For the same density, the escape velocity v_e and gravitational acceleration g_0 are $5.8\times 10^{-4}\times R$ m/s and $1.7\times 10^{-7}\times R$ m/s^2, respectively. Here R is the radius of the cometary nucleus. Since $g_0\,t \ll v_e \ll v$, eq. 21 simplifies to:

$$m_f = m_i\frac{v}{v_e}. \tag{24}$$

According to the sublimation model, the thermal velocity of the molecule relative to the nucleus is $\approx 0.5\,\mathrm{km\,s^{-1}}$; this velocity is quite small as the model does not include dust, which in reality leads to higher surface temperatures and hence to higher vaporization velocities than those derived with the model. In order to get a maximum estimation for the radius of the neutral cloud around the nucleus, the velocity corresponding to the equilibrium temperature without sublimation, $T_{\mathrm{eq}} = \sqrt[4]{(1-A)\cdot P_{\mathrm{sun}}/(16\pi d^2\sigma)}$, is used: $\approx 2\,\mathrm{km\,s^{-1}}$.

For a nucleus with a radius R of 63 m (the upper size limit for a comet which sublimates completely in case of isotropic sublimation), the mass of the largest possible fragment is about 55000 times larger than that of the inclusion, but only 2.7 % of the mass of the cometary nucleus. The mass fraction decreases to 0.4 % for $R = 100$ m and to 4×10^{-7} for $R = 1$ km.

Therefore unrealistic large numbers of inclusions are necessary to remove a large fraction of a comet larger than the size limit for destruction by sublimation alone. Consideration of thermal splitting with or without inclusions of different ices does not change significantly the upper size limit for comets which disappear during perihelion passage.

5.3 Other disruption mechanisms

Other mechanisms like collisions, explosions of volatiles below the surface, and fast rotation have been suggested as causes for cometary disruptions (see overview in Shestakova and Tambovtseva 1997). Of these mechanisms, collisions are too infrequent to destroy all ≈300 comets seen by spacecraft coronographs. Fast rotation of all fragments seems extremely unlikely, too. Explosions may be possible, but given that sungrazers at perihelion are heated up to a depth of less than a meter, it would be hard to explain why explosions occur much more frequently during the perihelion passage of a sungrazing comet than during the time comets spend further from the sun. The perihelion passage of a sungrazer lasts only a few hours or a few days. For a typical sungrazer orbit($q = 1.3\ R_{\mathrm{sun}}$), 50% of the sublimated material evaporates during 3 hours around perihelion.

We conclude that the size limits we derived for the destruction of sungrazing comets by sublimation and possibly by tidal disruption are the actual upper size limits of these comets unless some unknown highly efficient destruction mechanism exists.

6 Oxygen ion fluxes from sublimating comets at 1 AU

We now consider the possibility of detecting ions from disintegrating comets. We calculate ion fluxes an observer would measure at 1 AU in the ecliptic plane. Then we discuss the probability of a detection by an ion detector on a spacecraft located at 1 AU.

6.1 General considerations

For this work, all considerations are restricted to the average sungrazer orbit, derived by averaging the preliminary orbit elements of all sungrazers discovered till August 1999, (Douglas Biesecker, personal communication).

$$
\begin{aligned}
q &= (1.31 \pm 0.26)\, R_{\mathrm{sun}} \\
i &= (142 \pm 5) \\
\Omega &= (-1 \pm 19) \\
\omega &= (79 \pm 16)
\end{aligned}
$$

where the symbols have their usual meaning.

This orbit is plotted in Fig. 11. An instrument in the ecliptic plane will measure ions originating at the ascending note, which is at 2.19 $\mathrm{R}_{\mathrm{sun}}$.

The H_2O sublimation model provides $\dot{m}$ along the orbit. Since sungrazers pass the sun very closely, H_2O molecules will be photo dissociated rapidly. Scaling the photodissociation rate of $12.99 \cdot 10^{-6}\,\mathrm{s}^{-1}$ at 1 AU (Budzien et al. 1994) with d^{-2} shows an average lifetime of $\approx 7\,\mathrm{s}$ at 2 solar radii. Values from the same publication indicate that $\approx 85.3\,\%$ of all H_2O molecules are destroyed by photodissociation:

$$\mathrm{H_2O} + \gamma \rightarrow \mathrm{OH} + \mathrm{H}$$

As $\approx 95\,\%$ of the solar wind consists of hydrogen, cometary hydrogen cannot produce a measurable ion flux peak from the comet. $63\,\%$ of the OH molecules are destroyed by photodissociation, and this with an average lifetime of $\approx 33\,\mathrm{s}$ at 2 solar radii:

$$\mathrm{OH} + \gamma \rightarrow \mathrm{O} + \mathrm{H}$$

The neutral oxygen atoms will be rapidly ionized by photons or electron impact, and then follow the solar wind radially away from the sun. Therefore, different oxygen ions are the only particles originating from comet H_2O sublimation which might be measured at 1AU. We restrict our analysis to ions arriving at 1 AU close to or in the ecliptic plane. The slow speed solar wind has to be considered in this case. In order to find the charge state distribution

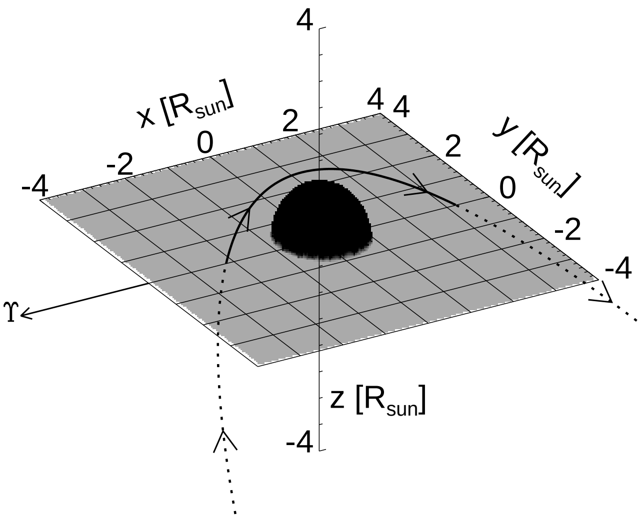

Figure 11: Averaged sungrazer orbit with $q = 1.3R_{\text{sun}}$. The ecliptic plane, the sun and the direction of the first point of Aries are shown. The ascending node is close to the first point of Aries ($\Omega \approx 0$) on the negative x-axis. In spring, we see the sun in the first point of Aries, so the earth is on the side of the descending node. Cometary ions can be measured in autumn when the earth is on the side of the ascending node.

expressed by the dimensionless occupation numbers $n_0(t), n_1(t), \ldots, n_8(t)$ for each charge state, the following system of coupled differential equations must be solved:

$$
\begin{aligned}
\dot{n}_0 &= n_e \cdot (-I_{0,1} \cdot n_0 + R_{1,0} \cdot n_1) - r_\gamma \cdot n_0 \\
\dot{n}_1 &= n_e \cdot (I_{0,1} \cdot n_0 - [I_{1,2} + R_{1,0}] \cdot n_1 + R_{2,1} \cdot n_2) + r_\gamma \cdot n_0 \\
\dot{n}_i &= n_e \cdot (I_{i-1,i} \cdot n_{i-1} - [I_{i,i+1} + R_{i,i-1}] \cdot n_i + R_{i+1,i} \cdot n_{i+1}) \quad \text{for } i = 2 \ldots 7 \\
\dot{n}_8 &= n_e \cdot (I_{7,8} \cdot n_7 - R_{8,7} \cdot n_8)
\end{aligned}
$$

with the normalization condition $\sum_{i=0}^{8} n_i = 1$. $n_e[\text{cm}^{-3}]$ is the electron density fitted as a function of d: $n_e(d) = 2.34 \cdot 10^{23} \cdot d^{-2}$ (Bochsler 2000). $I_{i,i+1}[\text{cm}^3\,\text{s}^{-1}]$ is the electron impact ionization rate from state i to state $i+1$. It is calculated with the method by Arnaud and Rothenflug (1985). $R_{i,i-1}$ is the electron recombination rate from state i to state $i-1$ (Nahar 1998). r_γ is the photoionization rate from neutral oxygen to O^+ and assumed to vary with d^{-2}. Scaling with a rate of $7.5 \cdot 10^{-7}\,\text{s}^{-1}$ at 1 AU (Rucinski et al. 1996) yields $r_\gamma = 1.68 \cdot 10^{16} \cdot d^{-2}$. Both $I_{i,i+1}$ and $R_{i,i-1}$ are functions of the electron temperature T_e, which is fitted by a function of d: $T_e(d\,[R_{\text{sun}}]) = 5.5 \cdot 10^{10} \cdot [5.49 \cdot 10^{-5} - (0.2+d) \cdot \text{e}^{-10d}]/d$ (Bochsler 2000). With this, the system of differential equations can be evaluated at a given perihelion distance

	O^{4+}	O^{5+}	O^{6+}
Relative distribution	0.215	0.605	0.180
Absolute ion flux	$1.0 \cdot 10^{11}$	$2.9 \cdot 10^{11}$	$8.6 \cdot 10^{10}$

Table 1: Charge state distribution and ion fluxes in particles per m^2 and s of the oxygen ions from a sungrazer with a nucleus of $\varrho = 600\,\mathrm{kg\,m^{-3}}$, $A = 0$ and initial radius 28 m.

d. Together with a velocity profile for the slow solar wind, $v_{\mathrm{sw}}(d)$ (Bochsler 2000), the system can be integrated from a starting distance d_0 out to 1 AU, yielding the probabilities $n_0, \ldots, n_8$ for an O^+ ion to arrive at 1 AU in the corresponding charge state.

Adding the lifetimes for the processes $H_2O \rightarrow OH \rightarrow O \rightarrow O^+$ shows that a H_2O molecule emitted from the nucleus at the ascending node produces an O^+ ion after only ≈ 2 minutes. Within this time, the nucleus moves only ≈ 0.07 solar radii. Therefore, ions to be measured at a spacecraft in the ecliptic plane originate from a very small orbit part around the ascending node (the descending node is excluded as no sungrazer was observed after the passage). Integrating the set of charge state equations beginning at the ascending node ($d_0 = 2.19 R_{\mathrm{sun}}$) yields the distribution in Table I.

6.2 Size of the cloud of sublimating material

An instrument in the ecliptic plane could potentially measure ions originating at the ascending node of the cometary orbit. An H_2O molecule leaving the nucleus at the ascending node of the average orbit has a lifetime of 8 s till photodissociating to OH. In order to get a maximum estimation for the radius of the neutral cloud around the nucleus, we use the expansion velocity corresponding to the equilibrium temperature without sublimation of $\approx 2\,\mathrm{km\,s^{-1}}$. The photodissociation to OH leads to a velocity addition of $\approx 1\,\mathrm{km\,s^{-1}}$ (Johnstone 1991, Wu and Chen 1993). On average, the velocity vectors add up perpendicularly: $\sqrt{2^2+1^2}\,\mathrm{km\,s^{-1}}$.

The lifetime for OH is ≈ 40 s. The photodissociation to O again leads to a velocity addition of $\approx 1\,\mathrm{km\,s^{-1}}$ (Johnstone 1991). Finally, the lifetime for neutral oxygen is given by $(r_\gamma + n_e \cdot I_{0,1})^{-1}$: ≈ 64 s. Adding up the distances for the 3 phases shows that the radius of the neutral cloud around the nucleus is $\approx 2\,\mathrm{km\,s^{-1}} \cdot 8\,\mathrm{s} + \sqrt{5}\,\mathrm{km\,s^{-1}} \cdot 40\,\mathrm{s} + \sqrt{6}\,\mathrm{km\,s^{-1}} \cdot 64\,\mathrm{s}$ ≈ 262 km (maximum estimation for the average).

Once an oxygen atom has been ionized it will quickly lose its velocity relative to the solar wind flow. The initial velocity perpendicular to the solar magnetic field (which we assume to point radially away from the sun) is the cometary velocity component at $2.19\,R_{sun}$ of $v_{perp} = 322\,\mathrm{km/s}$. This will cause the ion to gyrate around a solar wind magnetic field line. For a magnetic field B of $9.6 \cdot 10^{-5}$ T (corresponding to 10 nT at 1 AU and an inverse square law dependence for B as a function of heliocentric distance), the radius of gyration for O^+ ions at the ascending node is $r_g = (m_O v_{perp})/(eB) \approx 560$ m, where m_O and e are the mass and charge of the oxygen ion, respectively. The time scale for this guiding-center pickup is about one gyration period $2\pi r_g / v_{perp} \approx 0.01$ s, so that onset of gyration can be considered as instantaneous. Since the gyration radius is small compared to the size of the oxygen cloud, any motion perpendicular to the direction of solar wind expansion can be neglected. Along the magnetic field lines newborn ions move with an initial velocity of 260 km/s towards the sun. They are decelerated and brought to solar wind velocity ($\approx$ 100 km/s directed away from the sun at $2.2R_{\rm sun}$) by outward propagating fluctuations in the solar magnetic field (e.g. Gaffey et al. 1988). While a quantitative treatment of this process is beyond the scope of the present paper, we expect acceleration to occur fast because of the high power of ion-cyclotron waves close to the sun. Hence in what follows we assume that the particles are captured by the solar wind immediately after ionization and move radially away from the sun with solar wind velocity instantaneously.

The mass in the particle cloud, with a fraction of 16/18 of oxygen, is estimated by $|\dot{m}| \cdot \tau$ with $\tau = 112\,\mathrm{s}$ the sum of the 3 lifetimes. At the beginning, the neutral cloud is idealized as spherical; when moving out after the ionization, it is enlarged proportionally to heliocentric distance in the two directions perpendicular to the radial direction. In the radial direction, there is an enlargement due to thermal velocity dispersion (which cannot take place in the two other directions as the ions are bound to the magnetic field lines by gyration). Hence the cloud results as a rotationally symmetric ellipsoid at 1 AU. Let a be the semi-minor axis in the two directions perpendicular to the radial direction and b the semi-major axis in the radial direction. Hence a is $\approx 262\,\mathrm{km}\cdot 1\,\mathrm{AU}/2.19R_{\rm sun} = 2.6 \cdot 10^7\,\mathrm{m}$. The kinetic temperature of oxygen ions in the solar wind is $\approx 2 \cdot 10^6\,\mathrm{K}$ (Hefti et al. 1998), implying a thermal velocity of $v_{\rm th} \approx 50\,\mathrm{km\,s^{-1}}$. This velocity distribution is dominated by damped alfven waves. The correlation length of the velocity fluctuations and its dependence on the distance from the sun is not well constrained in the inner heliosphere. From the available measurements reviewed in Tu and Marsch (1995) we estimate a correlation length of 2×10^9 m. We approximate the elongation b of the ellipsoid by a random walk with the step size being the linear expansion of the ions while traveling one correlation length and the number of steps being the number of correlation lengths in 1 AU:

$$b = v_{th}\frac{\lambda}{v_s}\sqrt{\frac{\Delta}{\lambda}} = \frac{v_{th}}{v_s}\sqrt{\lambda\Delta} \tag{25}$$

Here v_s is the solar wind velocity, λ the correlation length, and $\Delta = 1$ AU the distance of the observer from the sun. For $v_s = 400$ km/s, $v_{th} = 50$ km/s, and $\lambda = 2\times 10^9$ m, b is 2.2×10^9 m.

6.3 Fluxes, duration, and probability for a detection by a spacecraft at 1 AU

We now try to estimate if an ion detector on a spacecraft may be able to find ions originating from a sungrazing comet. We determine the oxygen flux at 1 AU and the probability that a spacecraft located at 1 AU in the ecliptic plane passes through a cloud of material evaporated from a sungrazing comet. We assume that the spacecraft is close to earth and at rest relative to earth.

The spacecraft crosses the ellipsoid in the direction of a with the orbital velocity of the earth, hence within $2a/30\,\mathrm{km\,s^{-1}} \approx 29$ minutes. In contrast, the ellipsoid needs $2b/400\,\mathrm{km\,s^{-1}} =$

3 hours to cross the line of 1 AU heliocentric distance. Therefore, the spacecraft is able to observe oxygen ions from a sungrazer during ≈ 29 minutes.

The longitude Ω of the ascending node directly indicates the position the spacecraft must have to be in the purely radial path of the ions. The average of Ω yields the date 22nd September and the standard deviation the period 3rd September to 11th October. The velocity v_r of the ions relative to the spacecraft is $\sqrt{400^2+30^2} \approx 400\,\mathrm{km\,s^{-1}}$. The average mass flux F (mass per area and time) of all oxygen ions at the spacecraft is the product of the mass density in the ellipsoid and v_r.

$$F = \frac{16/18 \cdot |\dot{m}| \cdot \tau}{\frac{4\pi}{3} a^2 b} \cdot v_r = 6.53 \cdot 10^{-18} \cdot |\dot{m}| \tag{26}$$

Evaluating Eq. 5 at the ascending node gives

$$|\dot{m}| = 13.9 \cdot (1-A) \cdot R^2 \tag{27}$$

R is the radius at the ascending node and can be calculated with Eq. 7: $R = R_0 + \int_{-\pi}^{-\omega} \frac{dR}{d\vartheta} d\vartheta = R_0 - 9290 \cdot (1-A)/\varrho$. Inserting this in Eq. 27 and then Eq. 27 in Eq. 26 yields:

$$\boxed{F(R_0, \varrho, A) = 9.1 \cdot 10^{-17} \cdot (1-A) \cdot \left(R_0 - 9290 \cdot \frac{1-A}{\varrho} \right)^2}$$

For a nucleus with albedo zero, a density of $600\,\mathrm{kg\,m^{-3}}$ and an initial radius just small enough to be vaporized completely at perihelion, $R_0 = 1/2 \cdot \Delta R(A=0, \varrho = 600\,\mathrm{kg\,m^{-3}}, q = 1.307 R_{\mathrm{sun}}) \approx 28\,\mathrm{m}$, Table I shows the oxygen ion fluxes, in particles per m^2 and s, at 1 AU for each charge state. The expected cometary fluxes of $\approx 10^{11}$ $\mathrm{m^{-3}}$ $\mathrm{s^{-1}}$ are approximately two orders of magnitude above the oxygen flux in the solar wind at 1 AU. Especially O^{4+}, which is virtually missing in the solar wind, could be detected easily. On the other hand, we note that the initial radius of the comet must be above 15 m. A smaller comet sublimates completely before reaching the ascending node.

From orbital geometry, the position the spacecraft must have to measure sungrazer oxygen ions is fixed, and hence also the approximative period during the year: 3rd September till 11th October. Therefore, a detection is a question of comet orbit timing: what is the probability that a sungrazer passes the ascending node in a period such that its oxygen ions can meet the spacecraft? Between 1996 and June 2001, about 300 sungrazers have been discovered. Some of them might be too small to reach the ascending node and therefore to be detected. On the other hand, SOHO might not have detected all sungrazers. For a rough estimate of the detection probability, we assume that there were 300 detectable sungrazers in the 5.5 years SOHO has been in operation.

Each sungrazer produces an ellipsoid of ions that needs ≈ 3 hours to pass the line of 1 AU heliocentric distance. If there were always at least 3 hours between the ascending node passage of two sungrazers – an assumption which is likely to be fulfilled –, then there would be ≈ 37.5 days per 5.5 years ($\approx$7 days per year) when a spacecraft would pass sungrazer oxygen ions around the 22nd September. This yields an estimation for the measurement probability: $\approx 1.9\,\%$ per year, restricted to the approximative period 3rd September till 11th October.

While the sublimation flux from a sungrazing comet at a heliocentric distance of 2 solar radii could be easily measured at 1 AU, a spacecraft located at 1 AU will pass through a cloud of material from a sungrazing comet of the Kreutz family only approximately once in 50 years.

7 Conclusions

Using an H_2O sublimation model for cometary nuclei, we have derived upper size limits for sungrazers which are completely destroyed during perihelion passage. Considering sublimation only, the size limits can be expressed by the following analytical approximation to our numerical model:

$$R_0 \leq \frac{P_{\rm sun}\cdot 0.85}{8\cdot\sqrt{2GM_{\rm sun}}}\cdot\frac{1-A}{\varrho L\sqrt{q}} \approx 10^9\cdot\frac{1-A}{\varrho\sqrt{q}}$$

By setting the albedo to zero and the perihelion distance to one solar radius, one gets a general restriction valid for all sungrazers completely destroyed by sublimation alone:

$$R_0 \leq 3.8\cdot 10^4\cdot\varrho^{-1}$$

For the density of porous ice, $\approx 600\,\mathrm{kg\,m^{-3}}$, which was derived for comet Shoemaker-Levy 9 in Asphaug and Benz 1996, the upper limit in size is $\approx 63\,\mathrm{m}$.

Depending on the spatial distribution of the sublimation and the density of the cometary ice, the upper size limit may be increased by tidal disruption of the comet. Sublimation pressure will inhibit tidal disruption of an isotropically sublimating comet. In the case of completely anisotropic sublimation (no activity on the night side of the comet), the size limit increases to ≈ 100 m (at 600 $\mathrm{kg\,m^{-3}}$)

We estimated a probability of $\approx 2\,\%$ per year, restricted to the approximative period around the 22nd September from 3rd September till 11th October, of a spacecraft detection of oxygen ions produced in the sublimation of a sungrazer. The duration of the passage of the spacecraft through the ion stream is ≈ 29 minutes. For the average sungrazer orbit, the charge state distribution of the oxygen ions is given in Table I. The total mass flux F for all charge states, in kg per m^2 and s, depends on the cometary properties R_0, ϱ and A and is estimated by

$$F(R_0,\varrho,A) = 9.1\cdot 10^{-19}\cdot(1-A)\cdot\left(R_0 - 9290\cdot\frac{1-A}{\varrho}\right)^2$$

For $R_0 = 28\,\mathrm{m}$, $\varrho = 600\,\mathrm{kg\,m^{-3}}$ and $A = 0$, the fluxes for the different charge states are given in Table I, in particles per m^2 and s, and are well above detection threshold. Unfortunately, the probability is quite low that a spacecraft actually passed through an ion cloud from a sublimated comet.

Comparing the absolute magnitudes of large sungrazers like Ikeya-Seki and Pereyra with those of the SOHO sungrazers shows a difference of about 15 magnitudes. This implies that the large sungrazers were $100^3 = 10^6$ times brighter. If this brightness can be scaled with the cometary surface, then Ikeya-Seki and Pereyra were approximately 1000 times larger than the SOHO sungrazers. This is consistent with a size for Ikeya-Seki and Pereyra of a few kilometers and a few meters for the SOHO sungrazers. Limiting the sizes of Ikeya-Seki and Pereyra to 10 km, and assuming this estimation is good within one order of magnitude, the brightness comparison provides additional evidence for a size of the SOHO sungrazers of less than 100 m.

If the SOHO sungrazers are fragments of a disruption several revolutions ago, they sublimated continuously by ΔR per orbit. In this case it seems unlikely, that all fragments disappear during the same orbit, as we observe now. Therefore, we conclude that the SOHO sungrazers are remnants of a disruption that occurred during the last perihelion passage, approximately 1000 or 2000 years ago. The huge number of remnants indicates that the parent body was highly fragile, presumably a rubble pile. The wide spread of the SOHO sungrazers along their orbit shows that the remnants are not gravitationally bound. Hence there must have been a mechanism that allowed the fragments to overcome the gravitational binding of their parent body. The acceleration due to the sublimation pressure is different for different fragments: The force varies with R^2, whereas the mass varies with R^3. Hence even two bodies of equal shape but different size will be accelerated differently and move away from each other, unless the sublimation pressure is too low to overcome gravitational binding. At this point, we cannot answer this question, but one destruction mechanism that explains the wide spread along the orbit, is tidal disruption. This would also explain why we see a more or less constant flux of sungrazers. A tidal disruption causes a wide spread of the cometesimals. On the other hand, it is unlikely that a nearly constant flux of 300 fragments can be produced by a thermal stress splitting.

Since tidal forces are too weak to disrupt any material of appreciable strength, the fragments of the tidal disruption of a comet cannot be smaller than the cometesimals of that comet. If the SOHO sungrazers were created by tidal disruption, their upper size limits are also upper limits for the size of the cometesimals of their parent body.

While the SOHO sungrazers would in this case consist of either a few or only one cometesimal, larger remnants still consist of many cometesimals and in some cases can be disrupted further by tidal forces. For example, comet Ikeya-Seki broke into three pieces when approaching perihelion. This is consistent with the scenario for the disruption of a rubble pile comet on Ikeya-Seki's orbit. Numerical solution of Eq. 19 predicts a mass of the largest remnant of about half the parent body mass for a tidal disruption on Ikeya-Seki's orbit ($q = 1.68\ \mathrm{R}_{sun}$). The condition for tidal breakup that tidal stress must be larger than sublimation pressure yields a lower limit for the size of Ikeya-Seki in the case of isotropic sublimation. Replacing R_{sun} in eq. 15 by the perihelion distance of Ikeya-Seki and assuming $\varrho = 600$ kg m^{-3} results in a radius of comet Ikeya-Seki of at least 3.5 km. We note that this limit is valid in the case of isotropic sublimation only.

The sungrazing state of comets is short-lived. A large sungrazer like the progenitor of the Kreutz-family disrupts into several large fragments with a size of perhaps a few kms and many small ones like the sungrazers detected by SOHO. While the small fragments do not survive the next perihelion passage, the large ones will be destroyed after several tens of orbits (corresponding to several 10^4 years for the Kreutz comets) if destructed by sublimation alone. If further disruption occurs (as in the case of comet Ikeya-Seki), the lifetime is even shorter. For this reason there are not many sungrazing comets visible at a given time although the sungrazing state may be a frequent cometary end state (Bailey et al 1992).

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