Chapter 3

Nucleus

The nucleus of a comet is typically a small body, ranging from a few hundred meters to some tens of kilometers in diameter [Festou *et al.*, 1993]. It consist of a mixture of ices, mainly water and carbon monoxide and a number of minor volatiles, and silicate dust particles.

Up to now only two cometary nuclei have been imaged directly. The first was the nucleus of comet P/Halley which was visited by five spacecrafts in spring 1986. The European probe Giotto and the Russian VEGA probes took the first direct images of a nucleus. The images showed an irregular ("peanut-shaped") nucleus with a size of approximate 15×7×7 km [Keller *et al.*, 1986]. The nucleus showed an average albedo of only 0.04, making it one of the darkest objects in the solar system.

15 years after Halley on September 23, 2001 the American spacecraft Deep Space 1 encountered comet P/Borrelly. The probe took a series of images of the nucleus of Borrelly, the last

Figure 3.1: Encounter sequence of comet Halley ([Keller *et al.*, 1986])

image from a distance of only 3616 km. Borrelly's nucleus is also irregular shaped ("bowling pin"-shaped) with a size of approximate 8×4×4 km. The first estimates for the albedo yielded an average of 0.04 with some dark patches of 0.02 [Soderblom *et al.*, 2001].

Figure 3.2: Final image of Borrelly's nucleus with a resolution of about 45 meters. The distance to the nucleus was 3616 km. The Sun direction is down and slightly out of the image plane. (Image courtesy of DS1 science team)

Solar flux irradiating on the surface of the nucleus leads to the sublimation of ices of the cometary material. The solar flux scales with the heliocentric distance as r_h^{-2}. Far from the Sun the comet is inactive. The activity starts as soon as the nucleus reaches a temperature high enough to sublime CO and other minor volatiles (N_2, CO_2, ..). CO is the most abundant of the highly volatile components with a sublimation temperature $T_{sub} = 24$ K. More volatile species like for example N_2 are found only in trace amounts. As the comet approaches its perihelion more volatiles subsequently start to sublimate, for example HCN with a sublimation temperature of 95 K. Finally at a heliocentric distance of 3–4 AU water sublimation starts. The sublimation of CO dominates the activity of the comet until the water sublimation starts. The cometary activity has entered the water dominated phase. During the perihelion passage the comet will loose its upper surface layers. Estimates range up to several meters of surface loss [Benkhoff and Huebner, 1995], depending on the sublimation model used. After the perihelion passage, as the heliocentric distance of the comet increases, the activity of the volatiles turns off in reverse order. Outside of 4 AU the cometary activity is again CO dominated. At large heliocentric distances finally the comet returns to its inactive state.

Equation (3.1) describes the energy balance on the nucleus surface (see also figure 4.1). The incoming solar flux leads to a heating of the nucleus surface. Some of this heat is transported into the nucleus by heat conduction. Another part is radiated back into space as thermal infrared radiation. The rest is used up by the sublimation process.

$$\frac{(1-A_v)\cdot F_\odot}{r_h^2}\cos\zeta_\odot = \epsilon\sigma T^4 + Z(T)H(T) - k_s\frac{\partial T}{\partial z}|_s \tag{3.1}$$

A_v	visual albedo
$F_\odot$	solar flux
r_h	heliocentric distance
$\zeta_\odot$	solar zenith distance
ϵ	infrared emissivity
σ	Stefan-Boltzman constant
T	surface temperature
Z	sublimation rate
H	latent heat of sublimation
k_s	thermal conductivity of the surface material
$\frac{\partial T}{\partial z}\|_s$	temperature gradient at the surface

The problem in using equation (3.1) is, that most of the parameters used are either unknown or at least highly uncertain. Two examples are the thermal conductivity k_s and the visual albedo A_v. The thermal conductivity k_s is unknown and can only be estimated based on studies of cometary analog material (for example the KOSI experiments: Lämmerzahl *et al.* [1995], Kührt *et al.* [1995] and many others) and theoretical studies (for example Bunch *et al.* [1998], Seiferlin *et al.* [1996]). The values range over orders of magnitudes. The MUPUS experiment on the Rosetta lander will allow to determine this parameter directly for the first time at least for one comet. The visual albedo A_v has been measured directly only for the two comets Halley and Borrelly, which have been visited by spacecrafts. Both measurements yielded extremely low values of 4% or less [Keller *et al.*, 1986; Soderblom *et al.*, 2001]. Still two values are a very small base for a statistic.

It is unlikely that the nucleus itself is a homogeneous body. If we assume that cometary nuclei have been formed by aggregation of smaller planetesimals this may result in chemical or physical inhomogeneities. Looking at the image of comet Borrelly (see figure 3.2) it seems that at least two different areas can be identified, a smooth brighter middle area and rougher darker regions on both ends. However it is dangerous to draw conclusions on the nucleus interior from the surface morphology. In 2005 the Deep Impact mission [A'Hearn and Deep Impact Project Team, 1999] will hopefully provide some insights in the interior of the nucleus of comet Tempel 1. The Deep Impact probe will use a copper impactor to create a crater on the cometary nucleus.

Even if the nucleus was completely homogeneous after its formation, it will be altered by each passage close to the Sun. Assuming a porous nucleus structure volatiles can sublimate from deeper parts of the nucleus as well. Depending on the heat conduction of the cometary material the heat wave extends into the interior. This leads to the formation of sublimation fronts for each volatile. The sublimation front for a specific volatile is defined by the depth below which the temperature is too low to sublimate this volatile. Looking at figure 3.3 it is possible that regions of the nucleus are depleted of a volatile. In the example after some orbits the upper layers are depleted of the highly volatile CO. While the differentiation of the nucleus is a plausible assumption there are no observational evidences yet. For a more detailed discussion on sublimation models see Benkhoff and Huebner [1995] or Enzian [1997].

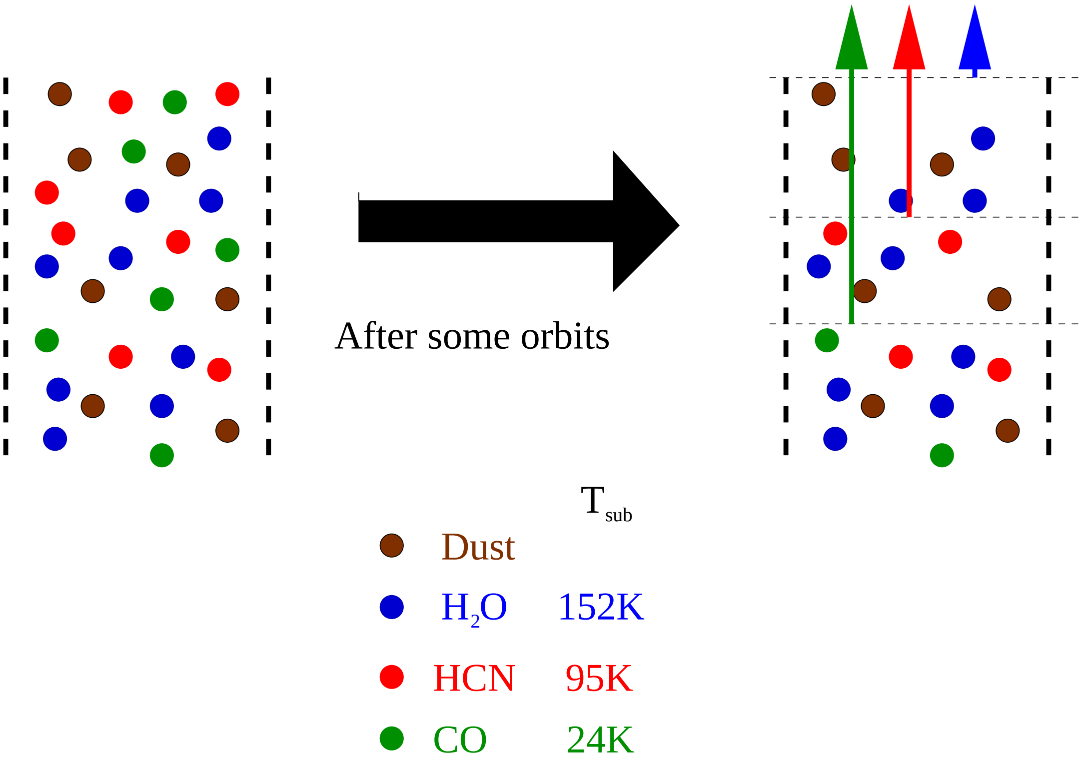

Figure 3.3: After some orbits the upper layers are depleted of the most volatile materials. (Drawing based on [Rauer, pers. comm.])