HYDRATED SILICATES ON EDGEWORTH-KUIPER OBJECTS – PROBABLE WAYS OF FORMATION

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Abstract. Visible-range absorption bands at 600–750 nm were recently detected on two Edgeworth-Kuiper Belt (EKB) objects (Boehnhardt et al., 2002). Most probably the spectral features may be attributed to hydrated silicates originated in the bodies. We consider possibilities for silicate dressing and silicate aqueous alteration within them. According to present models of the protoplanetary disk, the temperatures and pressures at the EKB distances (30–50 AU) at the time of formation of the EKB objects (10^6 to 10^8 yr) were very low (15–30 K and 10^{-9}–10^{-10} bar). At these thermodynamic conditions all volatiles excluding hydrogen, helium and neon were in the solid state. An initial mass fraction of silicates (silicates/(ices + dust)) in EKB parent bodies may be estimated as 0.15–0.30. Decay of the short-lived ^{26}Al in the bodies at the early stage of their evolution and their mutual collisions (at velocities $\geq$1.5 km s^{-1}) at the subsequent stage were probably two main sources of their heating, sufficient for melting of water ice. Because of the former process, large EKB bodies ($R \geq 100$ km) could contain a large amount of liquid water in their interiors for the period of a few 10^6 yr. Freezing of the internal ocean might have begun at $\approx 5 \times 10^6$ yr after formation of the solar nebula (and CAIs). As a result, aqueous alteration of silicates in the bodies could occur. A probable mechanism of silicate dressing was sedimentation of silicates with refractory organics, resulting in accumulation of large silicate-rich cores. Crushing and removing icy covers under collisions and exposing EKB bodies' interiors with increased silicate content could facilitate detection of phyllosilicate spectral features.

1. Introduction

Edgeworth-Kuiper Belt (EKB) objects orbit the Sun outwards of Neptune's orbit, 30 AU to 50 AU, and are possibly rather primitive solid bodies. According to presently accepted notions, the EKB objects formed *in situ* (Safronov, 1996; Farinella et al., 2000), though some part of their material could be brought by projectile bodies from the formation zones of giant planets, mainly of Neptune and Uranus. Contemporary models of the solar nebula (Makalkin and Dorofeeva, 1996; Mousis et al., 2000) yield very low temperatures and pressures of T = 15–30 K and $P = 10^{-9}$–10^{-10} bar at the radial distance of 30–50 AU and the nebula

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age of about 10^6–10^7 yr when the EKB bodies of sub-planetary size were formed. At these T–P conditions all volatiles excluding hydrogen, helium and neon were in the solid state (mostly ices and some organics), and the abundance of rocky (silicate) dust component was lower than that of ices in accordance with the solar ratios of corresponding elements. Nevertheless, the detected probable signs of hydrated silicates on some EKB objects (Boehnhardt et al., 2002) show that silicates in the bodies may be sufficiently abundant to be detected and that the silicates are probably aqueously altered (e.g., Vilas and Gaffey, 1989; Busarev and Taran, 2002). We have tried to indicate possible processes responsible for accumulation and aqueous alteration of silicates in EKB bodies. Obviously, a necessary condition for the last process should be a liquid state of water that requires a considerable elevation of temperature in the bodies' interior. Plausible factors for heating were decay of radionuclides (short-lived ^{26}Al and long-lived ^{40}K, ^{235}U, ^{238}U and ^{232}Th) dispersed in silicate matter and mutual collisions between the bodies. As shown in model calculations, the long-lived radioisotopes were insufficient for total melting of ice fraction in icy satellites of giant planets of radii up to 800 km, although partial melting was possible (Consolmagno and Lewis, 1978; Prialnik and Bar-Nun, 1990). A considerable role of collisional events in the EKB is probably confirmed by strong correlations between observed B–V and V–R colors of EKB bodies and their calculated mean random collision speeds (Stern, 2002). A basis for these calculations is the collisional resurfacing hypothesis. It suggests that the flux of cosmic rays darkening and reddening the upper layer of surface of icy airless bodies competes with impacts that excavate fresh material (more bright and blue or grey) from the interior to the surface (Luu and Jewitt, 1996).

It is theoretically possible that phyllosilicates formed in the solar nebula at the earlier stage of its evolution, when $T \leq 400$ K (Drouart et al., 1999), before accretion of planetesimals (e.g., Prinn and Fegley, 1989; Ganguly and Bose, 1995). In this case the mechanism of phyllosilicate formation was the interaction of silicate dust with water vapor, but the contribution of the process remains unclear.

2. Some Estimates of Silicate Fraction in Sub-Planetary Bodies

Composition of EKB bodies can be roughly estimated from the data on the most primitive objects in the Solar system – comets and interplanetary dust particles (IDPs) (e.g., Delsemme, 1988; Jassberger et al., 1988; Kissel and Krueger, 1987; Mumma et al., 1993; Pollack, 1994; Greenberg, 1998), using the solar system elemental abundances (Lodders and Fegley, 1998). According to the data, the bodies may consist of refractory dust and volatile ices with dust to ice mass ratio varying within 0.5–1.3. Dust contains inorganic (48–58 wt.%) and refractory organic fractions. Variations in the mass fraction of the former are caused mainly by the uncertainties of abundance ratios of Fe/Si and Mg/Si (from 0.34–0.5 to 0.9–1). Inorganic fraction or rock consists of silicates (mainly of magnesium and iron silicates with mol relation FeO/(FeO + MgO) = 0.2–0.3), troilite (FeS) and metallic iron. Refractory organic fraction or CHON (52–42 wt.% in dust) is a complex insoluble polymer material with vaporization temperature ~400–600 K. It includes aliphatic, cyclic and aromatic hydrocarbons (PAH), the last being probably the main component. The relative proportions of elements in this fraction are estimated as C:H:O:N = 1:1:0.5:0.12 (Jessberger et al., 1988). CHON contains about 50–70% of the total amount of C in comets. Ices include water ice (up to 80 wt.%), the volatile organics (~10 wt.%) and gases (~10 wt.%). Volatile organic compounds are methanol, formaldehyde and others with vaporization temperature near 300 K at normal pressure; gases (CO, CH_3OH, CH_4, H_2S, HCN and others) were incorporated with water ice in the gas-dust protoplanetary disk at $T < \sim 50$ K (Fegley, 1999).

Thus, the mass fraction of silicates (silicates/(ices + dust)) in parent EKB bodies may be estimated as 0.15–0.30. Such a low content of silicates in the bulk of EKB objects makes their easy detection by remote sensing methods questionable, especially in presence of the dark CHON-component in the material. Nevertheless, absorption bands at 600–750 nm were found recently in reflectance spectra of two EKB objects (Plutinos 2000 GN_{171} and 2000 EB_{173}) (Boehnhardt et al., 2002). Taking into account the discovery of H_2O ice on EKB objects (e.g., Brown et al., 1999), one could consider the absorption bands as probable signs of hydrated silicates on the bodies. The spectral features are typical for Fe(2+)–Fe(3+) bearing phyllosilicates. Similar absorption bands were found in reflectance spectra of C–PD–J–G-type asteroids (Vilas and Gaffey, 1989), hydrated M–S-type asteroids and carbonaceous chondrites (Busarev and Taran, 2002). A strong correlation between the spectral feature at 700 nm and the characteristic absorption band of OH groups at 3 μm was found for low-albedo asteroids (Vilas, 1994; Howell et al., 2001). We have predicted a possibility of silicate features' detection in reflectance spectra of EKB objects (Busarev, 2001). If the interpretation is correct, the detected spectral features point to aqueous alteration and dressing of silicate matter in EKB bodies during their evolution. Removing external ice covers and exposing EKB bodies' nuclei with elevated silicate content under subsequent collisions could facilitate detection of corresponding spectral features. We consider possible mechanisms supporting the processes.

3. ^{26}Al and Related Water Ice Melting, Aqueous Alteration and Sedimentation of Silicates in the EKB Bodies

Among other radionuclides ^{26}Al (half-life 7.2×10^5 yr) could play a key role in heating and initial thermal evolution of the main-belt asteroids and other sub-planetary bodies (up to hundreds-km-size) because it is widespread in the interstellar medium as a product of galactic supernovae and novae evolution. It was discovered in the galactic equatorial plane in the proportion of $^{26}\mathrm{Al}/^{27}\mathrm{Al} \sim 10^{-5}$

(Mahoney et al., 1984) comparable to the same ratio (5×10^{-5}) in the Ca–Al-rich inclusions (CAIs) (at the time of their origin) of the Allende meteorite (Wasserburg and Papanastassiou, 1982). Moreover, the detection of ^{26}Mg (the decay product of ^{26}Al) in a differentiated meteorite (Srinivasan et al., 1999) confirms the role of ^{26}Al for heating and differentiation of the parent bodies of the main-belt asteroids. But was the concentration of captured ^{26}Al sufficient for melting water ice in the EKB objects? If the time of EKB bodies' formation was substantially larger than the half-life of ^{26}Al, then independently of the isotope concentration it couldn't heat the EKB bodies with high efficiency, for instance, as it heated parent bodies of the main-belt asteroids.

The formation time of hundreds-km-sized EKB bodies was from about one million years (Weidenscilling, 1997) to several tens of million years (Kenyon and Luu, 1998). It is assumed that the accretion of EKB objects was terminated by the formation of Neptune (Farinella et al., 2000) which began to disperse them *via* gravitational scattering. In this case an upper limit for accretion time of the EKB objects would be the formation time of Neptune, estimated as about a few 10^7 yr (Brunini and Fernandes, 1999; Bryden et al., 2000) to 10^8 yr (Pollack et al., 1996; Farinella et al., 2000). These timescales are at least one order of magnitude shorter than in previous models (Safronov, 1969; Wetherill and Stewart, 1989) due to incorporation of the stage of accelerated "run-away" accretion of giant planet embryos. Taking into account the model of cometary bodies formation by Weidenscilling (1997), accretion of bodies up to 100 km in radius at the EKB distances 35–50 AU within $\approx (1\text{–}1.5) \times 10^6$ yr seems to be possible, though this time is near the lower limit of accretion timescales. In this consideration we suppose that formation of planetesimals at the radial distances of the EKB could begin several 10^5 yr after the collapse of the protosolar cloud. Probably, this time was sufficient for formation of the protoplanetary disk and transport of the dust to the EKB distances.

If the accretion of bodies of radius $R = 100$ km was complete no later than a few ^{26}Al half-life times, the decay of this isotope provides enough heat to melt the water ice in the interiors of these bodies. To check this conclusion we adopt the mass fraction of rock component of 30 wt.% (in accordance with data in the previous section). The rock component with chondritic (solar) abundances of refractory elements contains 1.3 wt.% of aluminum. We also adopt the ^{26}Al/^{27}Al ratio of 1×10^{-5} which is obtained from the "canonical" initial ^{26}Al/^{27}Al ratio of 5×10^{-5} and accretion time of a EKB body as $\tau_a \approx 1.6$ Myr (after CAIs). This time possibly but not necessarily coincides with the age of the solar nebula (from the collapse stage).

The above figures, giving the ^{26}Al abundance, should be added with the decay energy of ^{26}Al = 3 MeV per atom and its decay constant $\lambda = 9.63 \times 10^7$ yr^{-1} to yield the heat production rate $Q = 0.40$ J kg^{-1} yr^{-1}. The time τ_m required to heat a large EKB body to the water-ice melting point and to melt the ice in its interiors can be estimated from the equation

$$\int_0^{\tau_m} Q \exp(-\lambda t) dt = \int_{T_0}^{T_m} c_p dT + L_f m_w, \tag{1}$$

where T_0 = 30 K is the adopted value for the initial temperature of the body, T_m = 273 K is the melting temperature of water ice (a good approximation to at P < 25 MPa, characteristic for interiors of the EKB body of radius $R \leq 300$ km), $L_f = 3.34 \times 10^5$ J kg^{-1} is the latent heat of fusion for H_2O, m_w = 0.38 is H_2O mass fraction (as we take for calculation), c_p is the thermal capacity at constant pressure per unit mass for the body's material. With some overestimation of c_p at temperatures from 30 to 150 K we can take the temperature dependence of specific heat values for all main components similar to that for water ice: c_{pw} = 7.67 T J kg^{-1} K^{-1} (Hobbs, 1974). In this approximation we obtain the following values of thermal capacities (all in J kg^{-1} K^{-1}): $c_{p\ \mathrm{r}}$= 3.1 T for rocks (mainly silicates), $c_{p\ \mathrm{CHON}}$= 5.7 T for refractory organics, and $c_{p\ \mathrm{vol}}$= 10 T for volatile organics and gases (the approximation for gases is most crude, but this has little effect due to their low content). We use also mass fraction of CHON m_{CHON} = 0.22 and combined mass fraction of volatile organics and gases $m_{\mathrm{vol}+g}$ = 0.10. With these values we obtain the thermal capacity for the mixture $c_p \approx c_{p0}T$, where c_{p0} = 6.1 J kg^{-1} K^{-2}. After substitution of this value in Equation (1) and integration we have the estimation for the time τ_m:

$$\tau_m = -\lambda^{-1} \ln\{1 - \lambda[c_{p0}(T_i^2 - T_0^2)/2 + L_f m_w]/Q\} \approx 1.9 \times 10^6 \,\mathrm{yr}. \tag{2}$$

Thus the water ice in the bodies can be melted in less than 2 million years after the body formation and, hence, at the age of the solar nebula of 3.5 million years. During this time only a surface layer of thickness $\Delta R \sim 10$ km could remain solid, as follows from the simple estimation

$$\Delta R \sim \sqrt{\kappa \tau}, \tag{3}$$

where κ is the thermal diffusivity related to the thermal conductivity k as $\kappa = k/(\rho c_p)$. The temperature dependence of κ for water ice is $\kappa = \kappa_0 T^{-2}$, where $\kappa_0 \approx 9.1 \times 10^{-2}$ m^2 K^2 s^{-1} (Kirk and Stevenson, 1987). However, the porosity of ices p = 0.5 decreases the thermal conductivity 5 to 50 times (Shoshany et al., 2002). The porosity would be at its maximum at the surface and reduces to the low values at the bottom of the layer. Thus the reasonable estimate for the thermal diffusivity of the layer is $\kappa \sim 10^{-6}$ m^2 s^{-1}.

The first outcome of radiogenic heating of the bodies (preceding the melting of water ice) should be evaporation of the most volatile species mentioned above as gases (CO, CH_3OH, CH_4, and so on). However their low integral fraction ($\approx$5 wt.%) and probable moderate to high porosity of the early EKB objects would minimize the effect of their separation on the structure of the bodies.

The consequences of water ice heating are much more important. First, huge amount of water ice evaporated at low pressures in the porous medium should recondense in the upper layers of the bodies, substantially reducing their porosity. As a result of insulation of the interiors from outer space, the pressure below the upper layer of thickness ΔR would become higher than 1 bar and melting of water ice should occur when heated to $T > T_m \approx 270$ K. Probable admixture of volatile organics might slightly decrease this temperature. Thus, as follows from Equations (1) and (2), internal water ocean in the young EKB bodies could form at their age $\tau_m \approx 1.9$ Myr, that is after $\tau_a + \tau_m \approx 3.5$ Myr after solar nebula CAIs and formation.

Consider the evolution of the internal water ocean in a young EKB body of R = 100–300 km. The thermal convection in the ocean should be vigorous, if the Rayleigh number Ra is much higher than its critical value $\mathrm{Ra}_{\mathrm{cr}} \sim 10^3$. We can estimate the value $\mathrm{Ra} = \alpha g d^3 \Delta T/(\kappa \nu)$, where $\alpha \approx 10^{-4}$ K^{-1} is the volumetric thermal expansion coefficient of the mixture, dominated by liquid water, g is the gravitational acceleration ($g \sim 4\bar{\rho} G R$), $\bar{\rho} = 1.4 \times 10^3$ kg m^{-3} is the mean density of the body (calculated at the above fractions of components), $d \sim 0.8$–0.9 R is the convective layer thickness, ΔT is the temperature difference across the layer, $\kappa \sim 10^{-7}$ m^2 s^{-1} and $\nu \sim 10^{-5}$ m^2 s^{-1} are the thermal diffusivity and kinematic viscosity of the water–solids mixture. At d = 70 km and the very low value of ΔT = 1 K we nevertheless obtain a very high value $\mathrm{Ra} \approx 10^{21}$. The Nusselt number (Nu), which is the ratio of the total heat flow (including convective one) to the conductive flow is related to Ra by (Schubert et al., 1979) $\mathrm{Nu} \approx 0.2\mathrm{Ra}^{1/3}$. With these data we can estimate the time scale for heat transport through the convective water ocean τ_c by relation (3) where ΔR is substituted for $d \sim 0.8$ R and the molecular thermal diffusivity κ is substituted for the effective thermal diffusivity κ_e which accounts for convection, with $\kappa_e = \kappa \cdot \mathrm{Nu}$. At the above parameters we obtain $\tau_c \sim 10^3$ yr. The time is very short relative to the time scale $\tau_m \sim 10^6$ yr which is also the time scale for heat transport through the outer body's shell of thickness $\Delta R \sim 10$ km and relative to the lifetime of the ocean till the onset of its freezing τ_0 (considered below). Owing to the rapid radial heat transport through the ocean its temperature is stabilized near the temperature of maximum water density ≈ 277 K (the adiabatic compression for hundreds-km-sized bodies is negligible) and probably never exceeds 280 K. After a lapse of time a continuing decrease of radiogenic heat production yields the freezing of the internal ocean beginning (as in a usual terrestrial ocean) from the upper layers.

The lifetime of the water ocean till the beginning of its freezing in the early EKB body of radius R can be estimated by comparing the heat flux F_1 from the ocean to the solid shell of thickness ΔR above it and the heat flux F_2 through the shell. The flux F_1 is generated in the interiors being heated by the ^{26}Al decay and quickly transferred to the lithosphere. Thus we can write

$$F_1 \approx \frac{1}{3}\bar{\rho}(R - \Delta R)Q\exp(-\lambda t) \tag{4}$$

on the assumption of ^{26}Al homogeneous distribution, where $\bar{\rho} = 1.4 \times 10^3$ kg m^{-3} is the mean density of the body (calculated at the above fractions of components). The flux F_2 can be written as

$$F_2 \approx k\Delta T/\Delta R, \tag{5}$$

where k is the thermal conductivity of shell, $\Delta T \approx 273 - 30 \approx 240$ K. We assume $k = 2$ W m^{-1} K^{-1} for water ice, taking into account the empirical relation for crystalline ice $k(T) = 567/T$ W m^{-1} K^{-1} and the compensating effect of increasing porosity from the base to the surface of the shell (Spohn and Schubert, 2003). The outer layer $\Delta R \sim 10$ km is of primordial composition, identical to the bulk one; thus we obtain $k \approx 1.5$ in the layer owing to the admixture of components other than water. The freezing of the water ocean begins when the incoming flow from interiors F_1 becomes lower than the flux F_2 coming from the shell. By equating two fluxes from (4) and (5) we obtain the estimate of the lifetime of the ocean of liquid water as $\tau_0 \approx 1.2$ Myr for the bodies of radius $R = 100$–300 km respectively.

This time is quite sufficient for silicates to form phyllosilicates by reaction with water. If the early EKB bodies, like comet nuclei, consisted of a conglomerate of ices and dust particles (the "dirty ice"), then sedimentation of solid particles (consisting of silicates and CHON) in the water ocean leads to formation of the core enriched in silicates (including phyllosilicates). However, convection hinders sedimentation and supports suspension. The criterion for sedimentation obtained by Solomatov and Stevenson (1993) includes the ratio of the settling velocity of particles in the non-convective medium u_p to the convective velocity u_c (Rouse numbers S):

$$S = \frac{u_p}{u_c}; \quad u_p \approx \frac{4g\Delta\rho r^2(1-\phi)^2}{150\bar{\rho}\nu_0\phi}; \quad u_c \sim \left(\frac{\alpha g d}{c_p}\frac{dF}{\bar{\rho}\nu}\right)^{1/2}, \tag{6}$$

where $\nu_0 \sim 10^{-6}$ m^2 s^{-1} is the kinematic viscosity of the liquid water with admixture (< 10 wt.%) of volatile organics, $\nu \sim 3$–$10\nu_0$ is the viscosity of the convecting liquid-solid mixture, $\Delta\rho \approx (2.2 - 1) \times 10^3 = 1.2 \times 10^3$ kg m^{-3} is the density difference between settling particles and fluid. (The particles contain silicate rocks and refractory organics (CHON) in proportion 0.57/0.43 by mass.) Parameter r is the radius of the settling particle, $\phi = 0.52$ is the mass fraction of the particles. The initial thickness of the internal ocean is taken as $d \approx 0.9R$. For the case of the early EKB bodies we assume that the thermal flux F is equal to F_1, where F_1 is defined by Equation (4). The thermal capacity c_p for the mixture of water and solids is taken equal to 2.4×10^3 J kg^{-1} K^{-1}. Values for parameters α and g are shown above. For the case of a low mass fraction ϕ of the settling particles ($\phi \ll 1$) Solomatov and Stevenson (1993) obtained the simple relation which we extend to the case of any $\phi < 1$ and obtain the following criterion for suspension (the case that sedimentation is inhibited):

$$S < \frac{r}{d}(\varepsilon \cdot \mathrm{Re})^{1/2}\frac{1-\phi}{\phi}, \tag{7}$$

where $\varepsilon \sim 0.01$ is the efficiency factor equal to the fraction of the maximum available power of the convection that is spent on the gravitational work against sedimentation, $\mathrm{Re} = u_c d/\nu$ is the Reynolds number. For the early EKB bodies we find $\mathrm{Re} \sim 10^{12}$ that is much higher than the critical value $\mathrm{Re}_{\mathrm{cr}} \approx 30$–$100$ for transition from laminar to turbulent convection. Thus the convection in the bodies is turbulent. With the parameter set for these bodies we obtain from (7) that sedimentation is inhibited for the particles smaller than ~ 10 cm, but takes place at $r > 10$ cm.

It is unclear whether the particles of rock composition can grow up to decimeter size even in 10^6 years, but the presence of the organic compounds in the solid particles can greatly increase their sticking probability, playing the role of a sticking agent in formation of rock-CHON aggregates.

The growth rate of the particle mass m and radius r at collisions with smaller particles is described by the simple accretion equation $dm/dt = \pi r^2 \phi \bar{\rho} u_r \beta$, where u_r is the mean relative velocity of particles, β is the sticking probability. For the parameters of the bodies under consideration, including velocities from (6), one can show that the time scale for the particle growth to decimeter size is rather low ($\sim$10 yr), if $\beta = 1$. The very low sticking probability $\beta \sim 10^{-8}$ is sufficient to reach $r \sim 10$ cm in 1 Myr. The settling time for the particles of $r \sim 10$ cm is much lower than 1 yr. Thus the formation of the core enriched in silicates and refractory organics could happen in the early EKB bodies during the lifetime of the water ocean of a few $\sim 10^6$ years. With the assumed mass fractions of the components we obtain the radius of the rock-CHON core $r_c \approx 0.7\ R$.

Because of their fluffy fractal structure some IDPs probably originated in the protoplanetary cloud (e.g., Rietmeijer and Nuth, 2001), organic coatings on silicate particles could not be an obstacle for penetration of liquid water to silicate particles and for the process of silicate hydration. The volatile organics dissolve in water, forming mineral acids. As is known from terrestrial conditions, an acidic medium accelerates transformation of inorganic compounds, in particular silicate hydration (Veselovskij, 1955). Three major hydrous minerals that are predicted to form in the sufficiently large planetesimals of the solar nebula are serpentine containing 13.0 wt.% H_2O, talc (4.8 wt.% H_2O), and brucite (8.3% H_2O) (Fegley, 2000). Hydrous phases similar to these minerals are found in CI and CM2 carbonaceous chondrites. Thus the silicates in the EKB bodies could contain about 10% of water.

From our estimates it follows that the processes of aqueous alteration of silicates and formation of the core were probably completed before the onset of the internal ocean freezing, which happened for the bodies of R = 100–300 km respectively at the time $\tau_a + \tau_m + \tau_0 \approx$ 1.6 + 1.9 + (1-2) = 4.5–5.5 Myr after formation of the solar nebula (and CAIs). This time is shorter than the formation period of giant planets (10^7 yr for Jupiter and Saturn and at least a few 10^7 yr for Uranus and Neptune). Hence the EKB bodies could become layered and have silicate-rich cores before the onset of their heavy bombardment by the bodies dispersed from the region of giant planet formation. The cores very probably contained phyllosilicates which could be exposed during the heavy-bombardment stage after many cratering and destructive events. Even at the zeroth sticking probability of the silicate-CHON particles the core could form in the early EKOs during the freezing of the water ocean by the following mechanism. At the top of the ocean a thin nonconvective layer exists because of the negative thermal expansion coefficient of water between 0 and 4 °C. By equating the thermal fluxes in the layer and in the upper ice shell with the help of Equation (5) we estimate the layer's thickness to be less than 1 km. According to our estimates the downward velocity of the upper boundary of the water ocean is less than the sedimentation velocity (Equation (6)) for particles of radius a few microns. So during the freezing of the ocean the particles concentrate in its lower, liquid fraction and form the core to the end of the ocean freezing. We find the duration of this process to be of the order of 10 Myr.

We considered a short accretion time scale of the EKB bodies which is slightly higher than the lower limit of the possible range of the accretion times. This means that we deal with a "border" case. So we can't fully rely on ^{26}Al as the main and only heat source for thermal evolution and hydrosilicate formation in the EKB bodies. Nevertheless, we suggest a possibility of radiogenic heat accumulation sufficient for origin of an aqueous media, aqueous alteration and sedimentation of silicates in the bodies of radius R = 100–300 km within the first 5–10 Myr of the solar nebula evolution Myr.

The effect of long-lived radionuclides at the stage of formation and early evolution of EKB objects is negligible relative to ^{26}Al (e.g., Choi et al., 2002). At timescales, comparable to the Solar System age, the long-lived radionuclides ^{40}K, ^{235}U, ^{238}U and ^{232}Th may have a dominant role in heating of the EKB objects, but the power of this heat source is sufficient to evaporate (partially or totally) only the ices more volatile than water ice (De Sanctis et al., 2001).

4. The Role of Collisions in Evolution and Silicate Aqueous Alteration in the EKB Objects

The relative velocities of the EKB bodies during the stage of their accretion should be lower than 50 m s^{-1}, as follows from the numerical models (Stern and Colwell, 1997a). This result is consistent with the theory (Safronov, 1969) at the value of Safronov number $\theta \approx 3$, where $2\theta = v_e^2/v^2$, v_e is the escape velocity from the largest body in the inverse power-law mass distribution, v is the mean square-root velocity of the EKB bodies relative to their mean circular Keplerian motion (it is assumed that the radii of the largest bodies in the distribution are about 100 km). Simple estimates show that for the initial stage the mean temperature increase of a EKB body in the distribution at such moderate-velocity collisions is less than 1 K, which is negligibly small for any cosmochemical applications.

The subsequent process was dispersion of EKB, when the growth of Uranus and Neptune gravitationally perturbed the orbits of the remnant bodies in their zones and ejected them to the EKB region. Their high-velocity collisions with the EKB bodies yielded not only erosion and fragmentation of the bodies, but also increased eccentricities of them up to 0.3 between 30 and 50 AU (Stern and Colwell, 1997b). According to results of these authors, no less than 99% of the original mass of the population was lost from the EKB during this stage of 10^9 yr (the mass decreased from 10–35 $M_\oplus$ to 0.1–0.3 $M_\oplus$). The relative velocities of collisions v at this stage, according to calculated eccentricities, could be higher than 2 km s^{-1}. A simple estimation of the mean increase of the body's temperature $\Delta T = T_2 - T_1$ can be made for collisions of large bodies of comparable masses. The energy balance can be expressed as

$$(m_1 + m_2)\int_{T_1}^{T_2} c_p(T)dT \approx \frac{1}{2}k_h\mu v^2, \tag{8}$$

where $\mu = m_1m_2/(m_1 + m_2)$ is the reduced mass, k_h is the fraction of impact energy converting to heat. The energy loss to fragmentation of the bodies and scattering of fragments is lower than the loss to the body's heating, as follows from many experimental and theoretic data. For large bodies we adopt k_h = 0.7–0.8. The heat capacity c_p for the assumed mixture of components of the early EKB bodies is approximated by the above finction: $c_p \approx 6.1T$ J kg^{-1} K^{-1}. For collisions with $v > 2$ km s^{-1} we obtain from (8) the temperature $T_2 \geq 500$ K, which is destructive for the hydrosilicates. However, bodies subjected to the high-velocity collisions, were mostly swept out of the EKB, and the remaining ones probably very rarely, if ever, experienced such impacts.

After accomplishing this destructive stage the EKB was close to the modern low-mass state with rather rare collisions onto 100-km-sized bodies. The collision lifetimes for disruption large objects in the present-day EKB are much longer than the age of the Solar System (Durda and Stern, 2000). The collision velocities in the EKB, as follows from the observed orbit eccentricities, are ≤ 1.5 km s^{-1}. The mean temperature rise ΔT at collisions with velocities v = 1.5 km s^{-1} we estimate from Equation (8) at 240 K, appropriate for hydrosilicate formation. The thermal consequences of mutual collisions of the EKB bodies include evaporation of volatiles, melting of water ice, impact dressing of silicates and creation of heat centers under the cratered areas which are "buried" for a long time in bodies' interiors and preserve favorable conditions for silicate hydration. However, kinetic restrictions on the processes in the subsurface layers of EKB bodies are to be studied. Collisions at such velocities lead also to erosion of EKB objects (Durda and Stern, 2000). Removal of icy covers of the bodies, excavation of phyllosilicates formed in their interiors and/or exposition of the interiors with higher silicate content were probable consequences of the events. The processed areas of the bodies would cover dozens of percent of their surfaces.

In the latest thermal models of comets, icy satellites of giant planets and EKB objects (e.g., Prialnik and Bar-Nun, 1990; De Sanctis et al., 2001; Choi et al., 2002) radiogenic heating is considered as the main factor of their evolution. In our opinion the effect of collisions of EKB objects on their thermal evolution was probably no less important than the decay of ^{26}Al. A combined effect of collisions, radiogenic heating, and (to less degree) of insolation could considerably increase the internal temperature of EKB objects (or some of them) from initial 15–30 K up to at least 210–240 K when a process of diagenesis (low-temperature aqueous alteration of silicates) (e.g., Rienieijer, 1985) could start. But as shown above, the temperature might have been substantially higher.

5. Conclusions

As follows from the above consideration, the interiors and/or undersurface layers of the EKB objects are the most proper places for formation of phyllosilicates. Two main mechanisms of heating of the bodies, partial evaporation and elimination of volatiles, melting of water ice and aqueous alteration of silicates probably existed. The first mechanism is the decay of radionuclides (mainly short-lived isotope ^{26}Al) in the rocky fraction of the EKB bodies during first 5 Myr after formation of the solar nebula (and CAIs). The melting of water ice and origin of internal water ocean in the sufficiently large bodies ($\geq$200 km) probably led to vast aqueous alteration of silicates. It could also yield the sedimentation of the silicate-organic fraction of matter and accumulation of silicate-rich cores. The second mechanism is the impact heating at the mutual collisions of the bodies with velocities $\sim$1.5 km s^{-1} at much later stage of their evolution.

There is a theoretical possibility of phyllosilicate formation in the solar nebula at the earlier stage of its evolution, before accretion of planetesimals, at interaction of the silicate dust grains with water vapor (e.g., Prinn and Fegley, 1989; Ganguly and Bose, 1995). However, if the temperature in the Kuiper-belt region never is higher than $\sim$150 K, H_2O was probably always in the form of ice. In this case the formation of phyllosilicates *in situ* in the gaseous nebular environment through the gas-solid reaction was impossible, and phyllosilicate formation could happen only in large bodies which could contain liquid water.

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