IRRADIATION EFFECTS IN COMET ICE: A SOURCE OF COMETARY CRYOVOLCANISM.

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Introduction: The source of cometary activity remains one of the main questions for small bodies science. It was found that a lot of comets show flash activity at large heliocentric distances, called cometary outbursts [1]. The outburst effect is caused by the spontaneous ejection of comet material from the surface, leading to an observed luminosity increase. Plenty of mechanisms have been proposed to explain this phenomenon: collisions of a comet with other small bodies, sublimation of CO and CO_2 ices, the polymerization of HCN and transition of the amorphous ice into the crystalline form [2]. The last one has been used in the cometary models to explain many detected outbursts far from the Sun (29P/Schwassmann-Wachmann 1, 1P/Halley, 95P/Chiron, and Hale-Bopp) [2]. However, amorphous-to-crystalline ice transition has strict temperature limitations: this effect is ineffective below 120 K. Also, the presence of amorphous ice in cometary ice has not been proved so far. It is significant to consider the impact of cosmic ray irradiation on the physical and chemical evolution of cometary material during long-term storing in the Kuiper Belt and the Oort Cloud [3]. Here, we study how the effect of radical accumulation under high energy proton irradiation at low temperatures induces fast energy release in ice. Many experiments have so far been carried out with water ice and solid methane irradiated by fast neutrons [4,5]. After accumulation of large dose or external warming, the neutron-irradiated samples demonstrated self-heating, called a "burp". Our experiments show that the process of radicals recombination in ice irradiated by cosmic rays (protons) may lead to impulses of fast energy release in comet nuclei.

Methods and Results: We developed the vacuum chamber for simulating the cosmic ray irradiation of water ice samples at low temperatures (80-85 K) and low pressure (0.01 mbar). After irradiation by 15 MeV proton beam, we slowly heat vacuum chamber to induce recombination of radicals. Accurate temperature measurements are used to detect energy release in irradiated ice. To do so, we also developed the temperature sensor running via Raspberry PI with external Copper-Constantan thermocouples.

Thermocouples detected additional energy release in the irradiated sample with the absorbed dose 1.3 eV $molecule^{-1}$ during slow heating compared to the calibration experiment (unirradiated ice) (Fig.1). Two peaks with the overall energy of 20 J/g took place at 84 and 107 K. We used the equation of a "thermal explosion" with a recombination reaction as an energy source to determine the rate and activation energy of recombination reactions [6]. From the analysis, the peak started at temperature 107 K relates to OH radicals activity, and the peak at 84 K is caused by recombination of H with OH radicals. Also, we detected thermal conductivity degradation of crystalline water ice after proton-irradiation. The decrease in thermal conductivity of the irradiated ice is supposed to be caused by an amorphization reaction - the destruction of the crystalline ice structure with amorphous ice production [7].

Discussion: The recombination of accumulated radicals can occur in comets located in the Kuiper Belt and the Oort Cloud subjected to long-term cosmic ray irradiation. Release of stored energy in the subsurface two-meter layer (from the efficiency of cosmic ray deposition [8]) can be stimulated by increasing solar radiation during sunward travelling or by a body impact. As a result, the recombination heats the comet layer and thus produce a sublimation of ices and frozen gases. The rate of recombination must be greater than the rate of thermal conductivity to trigger propagation of the recombination front. From Figure 2, this occurs at temperatures above 90 and 75 K, which are equal to heliocentric distances 9 and 14 AU (Halley's comet) for crystalline and amorphous ice, respectively. Using maximum accumulated energies in our experiment (20 J/g) and in neutron-irradiated ice at temperatures 20-50 K (150 J/g) [5], the area of comet subsurface layer subjected to recombination must be about 0.6–4.5 km^2 to stimulate detected outbursts. The fast recombination of trapped radicals can also start spontaneously upon achieving a critical concentration of radicals ≈ 1 % [5]. The time of such a concentration accumulation by GCRs in the subsurface layer is within the 10-150 Myr range. Thus, comets in the Oort Cloud and the Kuiper Belt may show activity even without external impacts. Also, the recombination reaction could induce the amorphous ice transition, thereby increasing released energy.

Conclusion: We have performed a laboratory study of energy accumulation in ice at low temperatures during high-energy proton irradiation. A similar process could occur in comet nuclei subjected to cosmic ray irradiation. We find that fast recombination of accumulated radicals in the comet layer is an efficient energy release process and could explain cometary outbursts at large heliocentric distances.

References: [1] Jewitt, D., Kim, Y., Mutchler, M., et al. 2021, AJ, 161, 188. [2] Gronkowski P., 2007, Astron. Nachr., 328, 126. [3] Maggiolo R., et al., 2020, ApJ, 901, 136. [4] Carpenter J. M., 1987, Nature, 330, 358. [5] Shabalin E., Kulagin E., Kulikov S., Melikhov V., 2003, Rad. Phys. Chem., 67, 315. [6] Kirichek O., Lawson C., Jenkins D., Ridley C., Haynes D., 2017, Cryogenics, 88, 101. [7] Fama M., Loeffler M., Raut U., Baragiola R., 2010, Icarus, 207, 314. [8] Gronoff G., et al., 2020, ApJ, 890, 89.

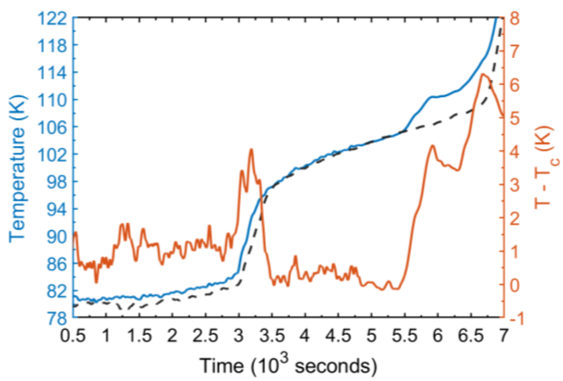

Figure 1. The energy release in ice during the heating after proton irradiation. The blue solid and black dashed curves correspond to the irradiated and unirradiated ice, respectively. The red curve gives the difference in temperature between the irradiated and control samples.

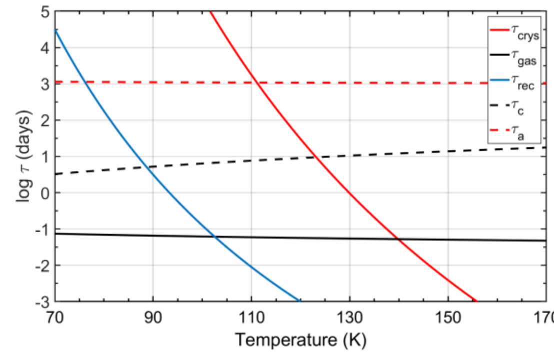

Figure 2. Timescales of the evolutionary process in comet nuclei: the recombination reaction (τ_{rec}), the amorphous to crystalline ice transition (τ_{crys}), the gas diffusion through two-meter porous material (τ_{gas}), and the thermal conductivity through a two-meter layer (τ_c for crystalline water ice, τ_a for amorphous water ice).