CONSTRAINING THE SURFACE AGES OF ICY OBJECTS IN THE OUTER SOLAR SYSTEM WITH COSMOGENIC LITHIUM, BERYLLIUM AND BORON
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Summary: Given current uncertainties in the cratering rates and geological histories of icy objects in the outer solar system, it is worth considering how the ages of icy surfaces could be constrained with measurements from future landed missions. In particular, we examine whether cosmic-ray exposure ages of surface deposits could be obtained by measuring the amounts of cosmogenic Lithium, Beryllium and Boron at various depths within a few meters of the surface.

Motivation: The icy worlds of the outer solar system exhibit a diverse array of geological histories, but there is still a great deal of uncertainty regarding when various surface features formed. Absolute ages of geological formations on icy bodies are often estimated using crater densities, and while different models of the impactor flux yield different age estimates, these calculations generally indicate that the most heavily cratered icy surfaces are comparable in age to the Solar System [1-3]. However, recent studies of the dynamical history of Saturn’s mid-sized satellites appear to contradict these calculations, since they suggest that many of those heavily cratered moons may be substantially less than a billion years old [4-5]. At the moment, it is not clear how to reconcile these two viewpoints.

Even if future analyses of the currently-available data are able to settle the debates regarding the ages of heavily cratered worlds, there are several objects in the outer solar system that have complex geological histories [6-10]. For these objects, a key unanswered question is how long they have been active and how long fresh material can be exposed on their surfaces before it is buried or recycled. Besides providing information about the geological history of these bodies, these timescales determine how long ago materials on the surface were in contact with liquid water reservoirs. This has implications for efforts to assess their habitability.

Future landed missions could potentially provide novel constraints on the age of icy surfaces, which would yield fresh insights into both the above topics. It is therefore worth considering what type of experiments such a lander could perform.

Proposed Approach: The most direct way to measure the absolute age of any solid material is with in-situ measurements of unstable isotopes and/or their daughter products. The Mars Science Laboratory recently measured the first radiometric age on another planet, demonstrating that such measurements can be performed by space missions [11]. There has also been a great deal of recent interest in a mission that would land on Europa and conduct extremely sensitive measurements of surface composition in order to ascertain whether life could exist beneath that world’s surface [12]. Hence it is worth considering what sort of experiments a lander could perform that would yield information about the age of the moon’s surface deposits.

Ice-rich surfaces will lack the long-lived isotopes typically used to radiometrically date objects from the inner solar system, so the most promising way to date ancient icy surfaces is with cosmic-ray exposure ages. The basic idea behind this method is that any exposed surface is constantly being bombarded with high-energy cosmic rays that cause nuclear reactions within the material. The concentration of the resulting cosmogenic nuclei near the surface steadily increases over time and can provide information about the age of the surface deposit. Such cosmic-ray exposure ages have been used to date various surface deposits on both the Earth and the Moon, and to determine when meteorites broke free from their parent asteroids [13-15].

Nuclear reactions induced by high-energy cosmic rays usually generate nuclei with atomic numbers comparable to or less than that of the original nuclei. Hence only elements with low atomic numbers are likely to be available for icy surfaces. Among these, isotopes of Hydrogen, Carbon, Nitrogen and Oxygen are probably not useful because these elements should be common native constituents of the ice, and so distinguishing any cosmogenic material will be extremely challenging. On the other hand, any Helium generated by cosmic rays should diffuse through ice on geological timescales, so this material will probably escape the surface. This leaves Lithium, Beryllium and Boron as the most promising elements for cosmic-ray exposure dating of icy surfaces. These elements are all found at comparatively low concentrations in chondrites, Earth’s crust and ocean water, and they are all chemically reactive species that can be retained in the surface for geological times.

In order to be able to use cosmogenic Lithium, Beryllium and Boron atoms to constrain the ages of surface deposits on icy bodies, two criteria need to be met. First, there must be a way to distinguish atoms produced by cosmic rays from atoms incorporated into the ice by other means. Second, the relevant instrumentation must be sensitive enough to detect the likely concentrations of cosmogenic atoms.

The first requirement can be achieved by sampling the relevant deposit at several depths within a few
meters from the surface. Cosmogenic atoms can be identified by measuring concentrations at various depths because the relevant cosmic rays can only penetrate a finite distance through the medium. The attenuation constants for the relevant cosmic rays in a wide range of materials is around 150 g/cm² [15-17], so the typical scale length for variations in the amounts of cosmogenic atoms within an icy regolith should be between 1 and 3 meters. Note that this is deeper than the regolith overturn depth of even ancient surfaces [18-20], but is still relatively shallow, and so could well be within the capability of a future lander.

The second requirement is more challenging, because the production rate of cosmogenic Lithium, Beryllium and Boron atoms in ice-rich materials is very low. Earth-based experiments using water tanks indicate that cosmogenic isotopes of Beryllium are produced at rates of around 50-100 atoms/gram of water per year [21-22], so the concentrations of cosmogenic Lithium, Beryllium and/or Boron in billion-year-old surfaces will be only a few parts per trillion. Any landed experiment will therefore have to be extremely sensitive to detect the relevant isotopes. While such low concentrations have not yet been measured in any spacecraft-based experiment, this particular investigation only requires measuring concentrations of chemically distinctive elements like Boron, Beryllium or Lithium (i.e. isotopic analysis is not required). Hence appropriate chemical separation and concentration techniques could potentially be used to obtain the required sensitivity levels. More investigation is therefore needed to ascertain whether this is within the capabilities of near-future missions to the outer solar system.

Conclusions: While there are some significant challenges associated with measuring the expected concentrations of cosmogenic Lithium, Beryllium and Boron, this currently appears to be the most promising way to directly constrain the age of surface deposits on icy worlds. Of course, further work is needed in order to identify experimental techniques that could achieve the desired sensitivities, evaluate the likely amounts of native atoms in relevant deposits, and accurately determine the relevant production rates.