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Review

Radioactive nuclei from cosmochronology to habitability

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This paper is dedicated to the memory of Gerald J. Wasserburg, who pioneered, built up, and inspired the science presented here.

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ABSTRACT

In addition to long-lived radioactive nuclei like U and Th isotopes, which have been used to measure the age of the Galaxy, also radioactive nuclei with half-lives between 0.1 and 100 million years (short-lived radionuclides, SLRs) were present in the early Solar System (ESS), as indicated by high-precision meteoritic analysis. We review the most recent meteoritic data and describe the nuclear interaction processes responsible for the creation of SLRs in different types of stars and supernovae. We show how the evolution of radionuclide abundances in the Milky Way Galaxy can be calculated based on their stellar production. By comparing predictions for the evolution of galactic abundances to the meteoritic data we can build up a time line for the nucleosynthetic events that predated the birth of the Sun, and investigate the lifetime of the stellar nursery where the Sun was born. We then review the scenarios for the circumstances and the environment of the birth of the Sun, within such a stellar nursery, that have been invoked to explain the abundances in the ESS of the SLRs with the shortest lives — of the order of million years or less. Finally, we describe how the heat generated by radioactive decay and in particular by the abundant ^{26}Al in the ESS had important consequences for the thermo-mechanical and chemical evolution of planetesimals, and discuss possible implications on the habitability of terrestrial-like planets. We conclude with a set of open questions and future directions related to our understanding of the nucleosynthetic processes responsible for the production of SLRs in stars, their evolution in the Galaxy, the birth of the Sun, and the connection with the habitability of extra-solar planets.

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1. Introduction

More than a century has passed since Marie Skłodowska Curie[1] coined the term Radioactivity to indicate the emission of radiation and particles from peculiar nuclei. Since then, the role and applications of radioactivity have had a profound impact in many fields of science and technology. The role of radioactive nuclei in the field of astrophysics has been long recognised and described. For example, radioactive nuclei power the light of supernovae and the radiation they emit can be mapped throughout the Galaxy by satellite observatories [1]. Here we focus on the most recent advances in the research directions that relate the process of short-lived (half-lives[2] $T_{1/2} \sim 0.1$ to 100 million years, Myr) radioactivity to the concept of *cosmochronology*, and on the relatively more recent link between short-lived radioactivity and *habitability*. We consider in particular the applications of radioactivity in the field of *cosmochemistry*, i.e., the study of the composition of meteorites and other solid Solar System samples aimed at explaining the origin of chemical matter in the Solar System and in the Universe. Due to extensive technological advances in the laboratory analysis of the isotopic composition of terrestrial and extraterrestrial materials, the amount of information and constraints that can be derived from such studies are expanding at a very fast rate. Much effort on the theoretical interpretation is needed to keep up with the experimental data. In this landscape, the connections between radioactivity, cosmochronology, and habitability are becoming more relevant than ever, and the implications of these connections are quickly becoming far reaching. The aim of this paper is to illustrate and discuss these connections and their implications.

Cosmochronology is intrinsically linked to radioactivity, being defined as the use of the abundances of radioactive nuclei to compute either the age of the elements themselves, or the age of astronomical objects and events. The first aim typically relies on very long-lived radionuclides with half-lives $T_{1/2}$ of the order of billions of years (Gyr), such as ^{238}U, ^{232}Th, ^{187}Os, ^{87}Rb; an introduction to this topic can be found, for example, in Chapter 1 of [1]. Here we address the second aim: to use radioactive nuclei to calculate the age of astronomical objects and events, specifically in relation to the birth of our Sun and Solar System, with the ultimate aim to compare the birth of our Sun to the birth of other stars and their extra-solar planetary systems. To such aim we use short-lived radionuclides (SLRs, $T_{1/2} \sim 0.1$ to 100 Myr), which provide us with a range of chronometers of the required sensitivity.

It is well known that radioactive decay can be used as an accurate clock because the rate at which the abundance by number of a radioactive nucleus $N_{\rm SLR}$ decreases in time due to its radioactive decay is a simple linear function of the abundance itself, where λ is the time-independent constant of proportionality referred to as the *decay rate*:

$$\frac{dN_{\rm SLR}}{dt} = -\lambda\, N_{\rm SLR}. \tag{1}$$

A quick integration between two set times t_1 and t_0 delivers:

$$N_{\rm SLR}(t_1) = N_{\rm SLR}(t_0)e^{-\lambda(t_1-t_0)}, \tag{2}$$

which can also be written as

$$t_1 - t_0 = \tau[\ln(N_{\rm SLR}(t_0)) - \ln(N_{\rm SLR}(t_1))], \tag{3}$$

1 The 150th anniversary of her birthday was recently celebrated on the 7th of November 2017.

2 See Table 1 for a list of all the symbols and the acronyms used throughout the paper.

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