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Deuteration of molecular clumps induced by cosmic rays

Sergio Pilling [a,*], Maurício Tizziani Pazianotto [b], Jose Manuel Quesada Molina [c]

[a] Universidade do Vale do Paraíba (UNIVAP), São José dos Campos, Brazil
[b] Instituto Tecnológico de Aeronáutica (ITA), São José dos Campos, Brazil
[c] University of Seville, Spain

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Abstract

The D/H ratio in astrophysical environments has instigated the scientists for at least 50 years. The wide range of values in the interstellar medium (ISM) from 10e to 7 to 10e-1 have usually been claimed to be due to small zero-point energy differences between reactants and products involving D and H (mainly at low temperatures). Here, we present a new source of deuteration processes in the ISM clouds as a result of cosmic ray irradiation. As a study object, we consider a typical molecular clump under the presence of incoming cosmic rays simulated computationally. The calculations were performed employing the Monte Carlo toolkit GEANT4 code (considering hadronic physics) and considering mainly the proton and alpha component of the incoming cosmic rays from the ISM (the dominant ones for the production of secondary protons and deuterons). The results suggest an increasing D/H ratio as function of time in the central part of molecular clumps (<200 AU) with the largest deuteration in the central region of the cloud, and a bump in the D/H ratio around 2–10 AU (which becomes more pronounced for clouds with larger timescales; > 10 Myrs). The results also show that for timescales between 10 and 100 Myrs the central part of the cloud has D/H around 6-16e-3, a value compatible with the observed D/H in some interstellar clouds. This work adds a new piece to the D/H puzzle of the ISM and might also help to explain the D/H ratio measured in different objects inside the Solar system.

Keywords: Astroparticle physics; (ISM:) cosmic rays; Nuclear reactions; Nucleosynthesis; Abundances; Software: simulations; ISM: clouds

1. Introduction

The study of the deuteration in astronomical objects, in particular the D/H ratio (deuterium-to-hydrogen ratio), has instigated the scientists for at least 50 years (e.g. Reeves & Bottinga, 1972; Rogerson & York, 1973; Laurent, 1983; Vidal-Madjar, 1991; Tielens, 1992; Sonneborn et al., 2000; Millar, 2005; Pettini et al., 2008; and references therein). The D/H ratio typically ranges from 8e to 7 (virtually absent; e.g. Canopus star Vidal-Madjar et al., 1988), passing through 2e-5 (the canonical interstellar medium (ISM) value; Sonneborn et al., 2000) and going up to 0.8 (some class 0/I proto-brown dwarfs Riaz & Thi, 2022). Additionally, as pointed out by Albertsson et al. (2013), the observations of deuterated species are also useful in probing the temperature, ionization level, evolutionary stage, chemistry, and thermal history of astrophysical environments.

The enhancement of the molecular D/H ratio compared to the primordial Big Bang nucleosynthesis value (~2.8e-5; Pettini et al., 2008) or ISM elemental value (~2e-5; Sonneborn et al., 2000), known as deuterium fractionation, is often attributed to a small zero-point energy differences between reactants and products in reactions involving D and H atoms (mainly at low temperatures) in the production of many of ISM molecules (e.g., Tielens, 1983; Dalgarno & Lepp, 1984). As discussed by (Millar, 2005),

* Corresponding author.
E-mail address: sergiopilling@yahoo.com.br (S. Pilling).

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