Numerical modeling of the solar modulation of helium isotopes in the inner heliosphere

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Abstract

In this work, a 3D numerical model is used to compute the modulation of galactic Helium isotopes from minimum activity in the previous A < 0 cycle, through solar maximum, and toward minimum activity in the current A > 0 cycle. A particular objective is to reproduce the main features of the $^3He_2$ to $^4He_2$ ratio observed by AMS02 at rigidities between 2.15 GV and 15.3 GV.

1. Introduction

The recent availability of AMS02 observations of the $^3He_2$ to $^4He_2$ ratio at rigidities between 2.15 GV and 15.3 GV with unprecedented accuracy over a long period of time reported by [1] unveiled new details whose main features warrant an investigation with our numerical model.

This paper focuses on the time and rigidity dependence of the modulation of $^3He_2$ and $^4He_2$ at the Earth from the period of minimum solar activity beginning at the end of 2006 until 2011, through the period of solar maximum activity from 2012 to just after 2014, and then for the beginning of the current period of minimum solar activity up to and including early 2017. This approach makes it possible to separate the modulation effects for $^3He_2$ and $^4He_2$ more accurately than before, taking into account effects caused by the difference in their respective VLIS's and those caused by the difference in their mass-to-charge ratio (A/Z), as well as what role changing solar activity may play in the then computed $^3He_2/^4He_2$. Understanding the rigidity dependence of this ratio in the inner heliosphere and subsequently that of p/He, opens up additional prospects to improve our understanding of the origin and propagation of GCRs in the galaxy and in the heliosphere.

2. Numerical model

The numerical model is based on solving the transport equation derived by [2] showing the four terms that represent the physical processes which CR undergo when they enter the heliosphere:

$$\frac{\partial f}{\partial t} = -(\vec{V}+\langle\vec{v}_D\rangle)\cdot\nabla f+\nabla\cdot(\mathbf{K}\cdot\nabla f)+\frac{1}{3}(\nabla\cdot\vec{V})\frac{\partial f}{\partial lnp} \quad (1)$$

where $f(\vec{r},P,t)$ is the CR distribution function, p is particle momentum, t is time, and $\vec{r}$ is the vector position in 3D with the three coordinates r, θ, and ϕ specified in a heliocentric spherical coordinate system where the equatorial plane is at a polar angle of $\theta = 90°$. The details of this numerical model together with the elements of the diffusion tensor and the VLIS's of both $^3He_2$ and $^4He_2$ have been published by [3-4].

3. Computed and observed spectra of $^3He_2$ and $^4He_2$

Figure 1 depicts the computed $^3He_2$ and $^4He_2$ modulated spectra with respect to their VLIS's as a function of rigidity in comparison with the corresponding observed AMS02 spectra at the Earth. The essence of this figure is to show that the $^3He_2$ and $^4He_2$ spectra from AMS02 are well reproduced by the model. These computations are obtained using the same set of modulation parameters, DCs and drift coefficient that reproduce the AMS02 proton modulation between 2011 and 2017 (see [4])

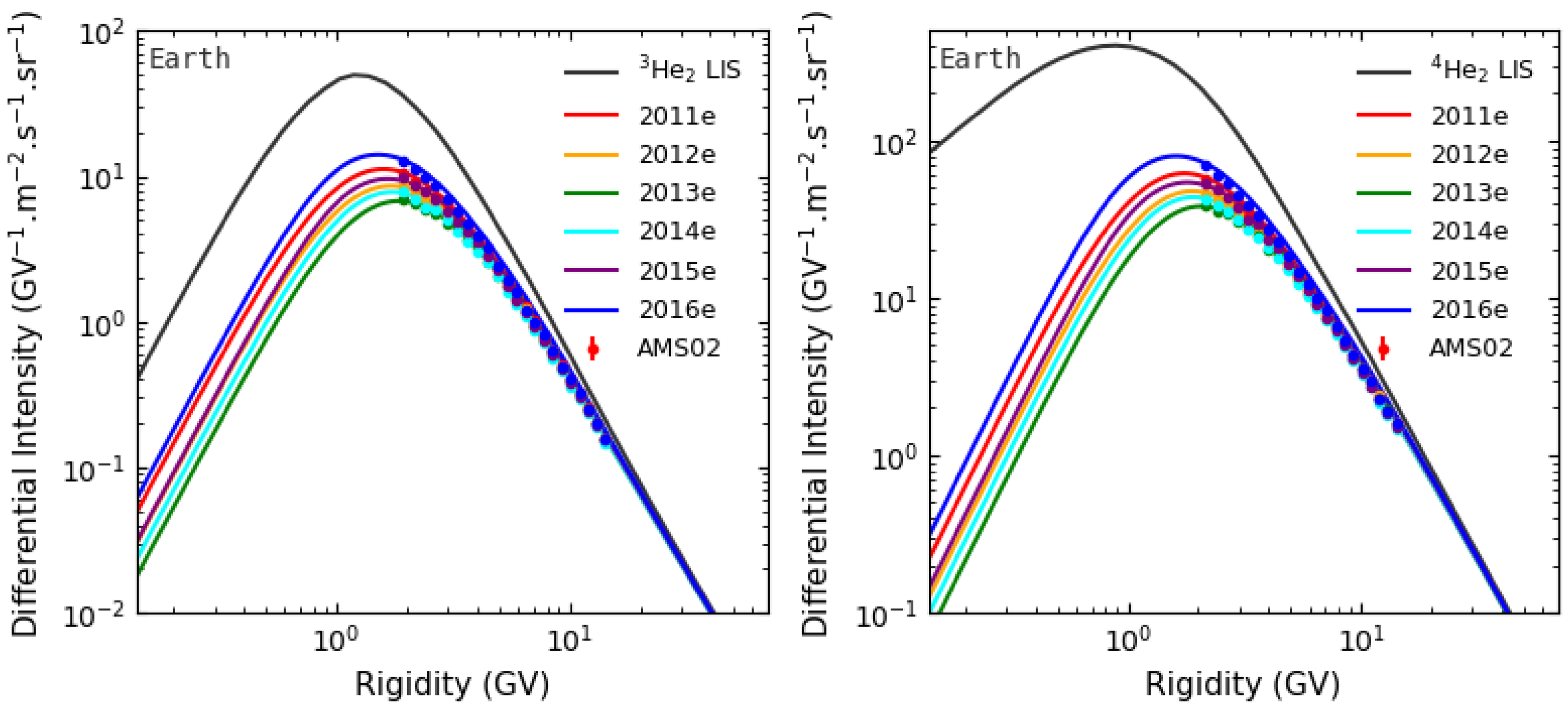

Figure 1: The modulated differential intensity for He3 (left panel) and He4 (right panel) computed as a function of rigidity for the time period between 2011 and 2016, compared to AMS02 observations reported by [1].

4. Computed $^3He_2$ to $^4He_2$ ratios

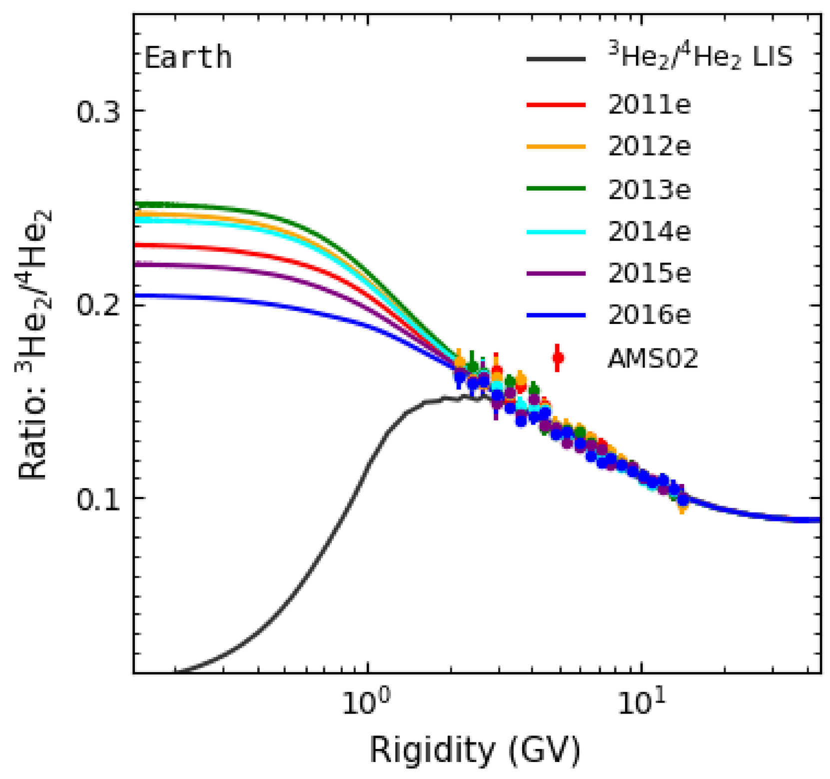

Figure 2: The computed $^3He_2/^4He_2$ ratios as a function of rigidity between 2011 and 2016 are compared with AMS02 observations from [1].

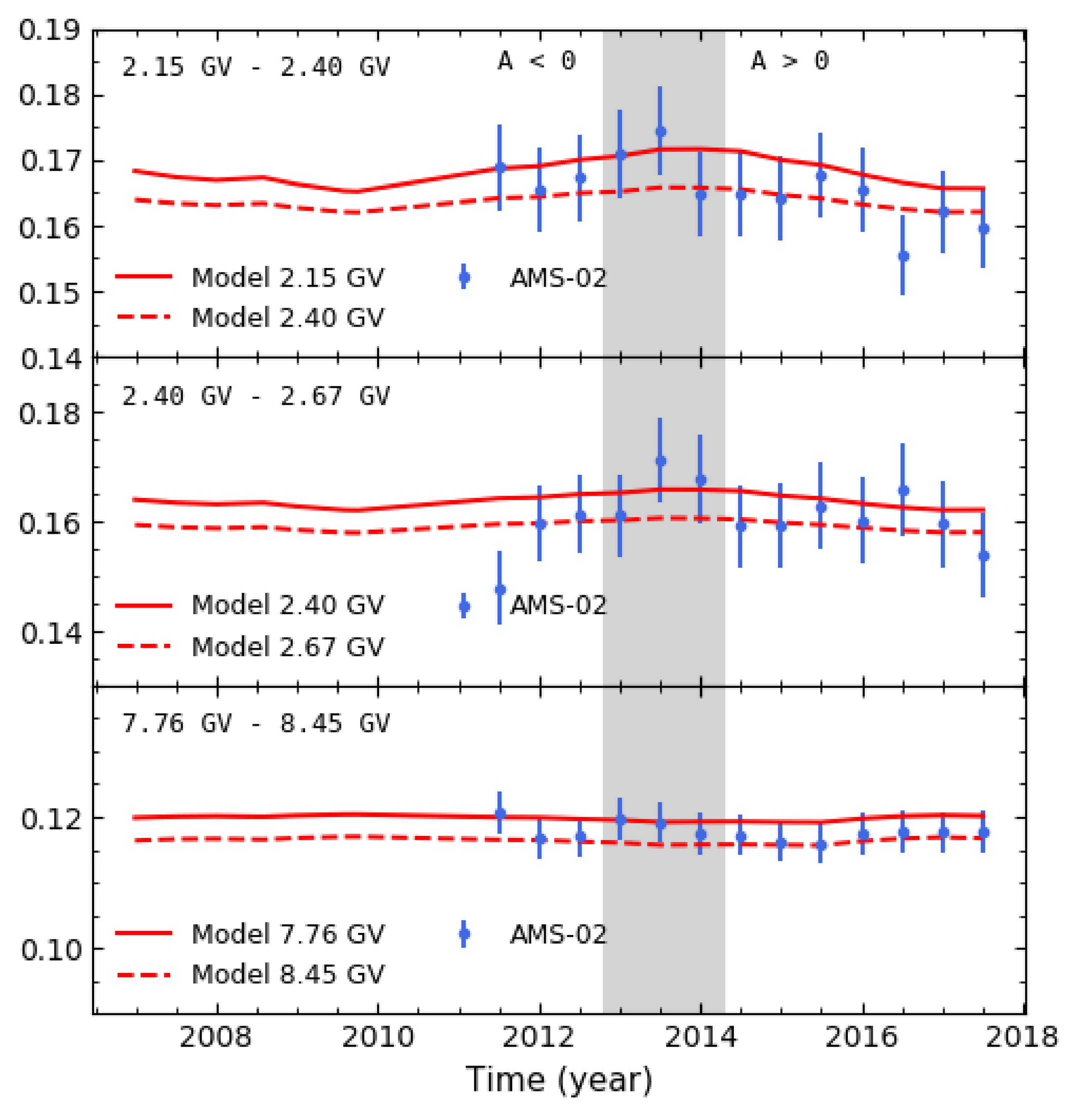

Figure 3: The computed $^3He_2/^4He_2$ ratio as a function of time together with AMS02 observations reported by [1].

5. Discussions and conclusions

The computed ratios, $^3He_2/^4He_2$, from 2011e to 2016e are shown at the Earth as a function of rigidity with respect to their corresponding VLIS's in Figure 2 and in comparison with AMS observations. **It follows that the numerical computations can reproduce convincingly the apparent single rigidity power law dependence, as well as the time independence of this ratio, above 4 GV.** Whereas below 4 GV, where there are not any AMS data, the computed ratios significantly decrease with decreasing rigidity from its maximum value reached during solar maximum conditions as represented by 2013e.

Figure 3 **shows that there is good compatibility between the time profiles of the computed and observed ratios**. To reproduce these observations, **we find that in addition to scaling down (up) the values of the diffusion and drift coefficients towards (after) the solar maximum, the rigidity slopes of the parallel and perpendicular DCs below 4 GV should change differently before solar maximum than afterwards.**

it is further noted that the $^3He_2/^4He_2$ for the period of decreasing (increasing) ratio coincide with the increasing (decreasing) intensities of both isotopes, which may well be a general modulation pattern.

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