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Towards understanding the time dependence of proton to helium ratios in the heliosphere

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A comprehensive three-dimensional numerical model for the modulation of cosmic rays in the heliosphere is applied to investigate the relative roles of the time dependence of the three diffusion coefficients on the p/He ratios at rigidities below 3 GV. At these rigidities the ratios have been observed by PAMELA and AMS to have a significant time variation. We find that the contribution of the time dependence of perpendicular diffusion in the radial direction of the heliosphere is the dominant cause of this observed time variation and not any fundamental difference between the solar modulation of galactic protons and helium.

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1. Introduction

The availability of precise and simultaneous measurements of the proton (p) to total Helium (He) ratio, (p/He), and the $^3He_2$ to $^4He_2$ ratio ($^3He_2/^4He_2$) by the AMS detector from 2011 to 2017 at the same rigidity [1] and p/He measured by PAMELA between 2006 to 2014 at a matching rigidity [2], provide prevailing evidence of a dependence on the mass-to-charge ratio (*A*/*Z*) and the very local interstellar spectra (VLIS) over a solar cycle. These observations revealed that both p/He and $^3He_2/^4He_2$ are not constant over time at rigidities below ~3 GV. In particular, it was shown for the current solar cycle that the ratios had decreased significantly from 2014, in the A > 0 magnetic field polarity cycle, in response to the declining level of solar activity [1]. Whereas above 2-3 GV both p/He and $^3He_2/^4He_2$ were found to be essentially unchanged thus far less dependent on the changing level of solar activity.

Recently, a report by [2] indicated that the time dependence of p/He observed by PAMELA below ~1.5 GV has a time trend that is different to that between ~1.5 GV and ~3 GV, with the former decreasing through the maximum solar activity period while the latter gradually increased from 2009 to reach a maximum at the end of 2013. Unfortunately, PAMELA observations of $^3He_2/^4He_2$ below ~1.5 GV is not yet available to confirm whether these different time trends also exist for $^3He_2/^4He_2$ based on a simultaneous investigation for both p/He and $^3He_2/^4He_2$ at this rigidity. However, the availability of reliable numerical modelling makes it possible to investigate this interesting time dependence simultaneously. In a first of our modelling reports on this topic, [3] argued and illustrated that these different time trends are the consequences of the effects of different *A*/*Z* for these GCRs but combined with the slopes of the modulated spectra at the Earth based on their respective VLIS's, and not due to any fundamental differences between the modulation of GCR protons and Helium. However, it is not yet established, at least not quantitatively, as to what extent individual elements of the diffusion tensor contribute to this interplay to reproduce the observed time trends in p/He and $^3He_2/^4He_2$, and in general for GCRs with dissimilar *A*/*Z*. This is the main purpose of this paper.

2. The numerical modulation model

The numerical modelling is done with a three-dimensional (3D) drift-model described and published by [3, 5, 6]. The parameters that are changed with time in the model, as proxies for solar activity to obtain the GCR results simulated in this study, are the observed magnitude B of the HMF at the Earth [http://omniweb.gsfc.nasa.gov] and its polarity change during solar maximum, and the changing HCS using α [http://wso.stanford.edu]. Additionally, the values and rigidity dependence of the three elements of the diffusion tensor and the value of the drift coefficient K_A together with the position of the solar wind termination shock are changed with time similar to [4, 5, 6]. These established changes in time and incorporated into the model are shown in Figure 1 with the three mean free paths (MFPs) and drift scale normalized relative to 2006e. Evidently, the three diffusive MFPs also change with time but maintain the same relative changes at 1 GV, in fact at all rigidities below 4 GV. The relative time changes in the drift scale is different than the MFPs. It remains to be established what specific modulation features arise when these MFPs do not maintain the same relative changes at lower rigidities where the observed ratios, p/He and $^3He_2/^4He_2$, indicate significant time dependences. The details of how these elements change is further discussed and shown below with emphasis on the simulated (computed) time dependence of p/He and $^3He_2/^4He_2$.

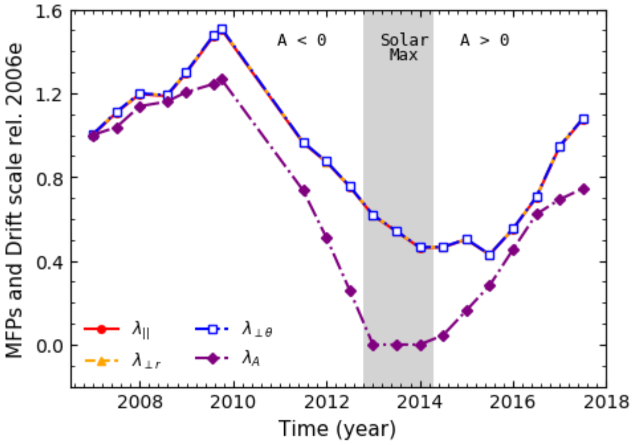

Figure 1: Normalized three MFPs ($\lambda_{\parallel}$, $\lambda_{\perp r}$, $\lambda_{\perp\theta}$) and drift scale (λ_A) at the Earth for 1 GV protons and Helium as a function of time relative to the end of 2006 (14 November - 12 December, 2006; 2006e) as they change for the A < 0 to the A > 0 HMF polarity epoch, respectively before and afterward the period of maximum solar activity when no well-defined HMF polarity was present (shaded band).

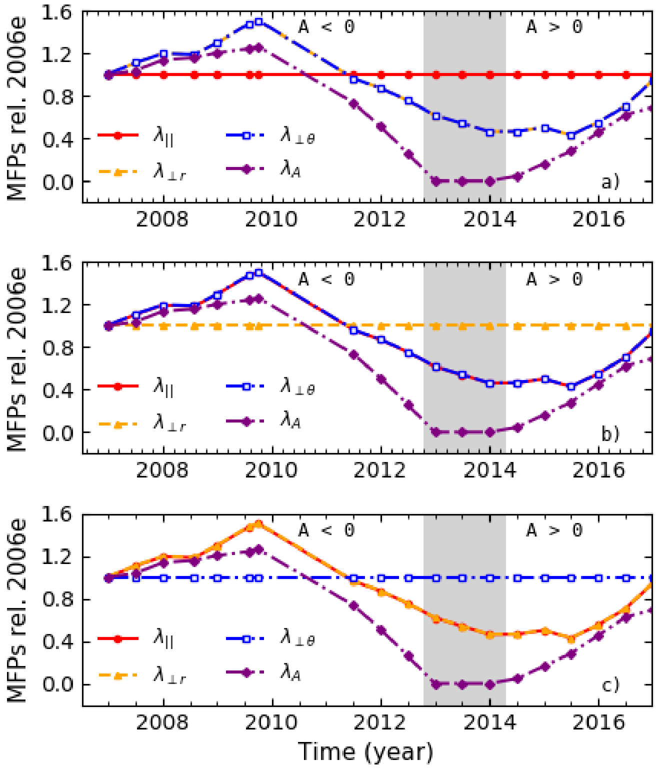

Figure 2: Three scenarios of the time dependence of the MFPs and drift scale, in units of AU, shown here at the Earth for a rigidity of 1 GV. In panels a), b) and c), $\lambda_{\parallel}$ (red), $\lambda_{\perp r}$ (orange), $\lambda_{\perp\theta}$ data as indicated by coloured circles and error bars.

2.1. Implications for the time dependence of the diffusion coefficients

To provide the context of using a numerical exercise for investigating the relative roles of the time dependence of the three MFPs related to the time variation of p/He and $^3He_2/^4He_2$ below 3 GV, they are kept unchanged one after another, each with time relative to 2006e. This is shown in Figure 2, first for $\lambda_{\|}$ (or $3K_{\|}/\beta/c$) (panel a), then $\lambda_{\perp r}$ (panel b) and $\lambda_{\perp\theta}$ (panel c), respectively. This way, the rigidity slope of the respective MFP is not changed at all with time, while the other modulation conditions and parameters, as well as drift scale, are scaled with time as in Figure 1. These simulations will be used to illustrate in terms of the relevant physics intrinsic to the numerical model, how the relation between the considered scenarios of time changes in the MFPs influence the trends in the behaviour of p/He and $^3He_2/^4He_2$. This will further clarify which of the three elements of the diffusion tensor plays a dominant role in shaping these time trends, especially before and after solar maximum activity periods.

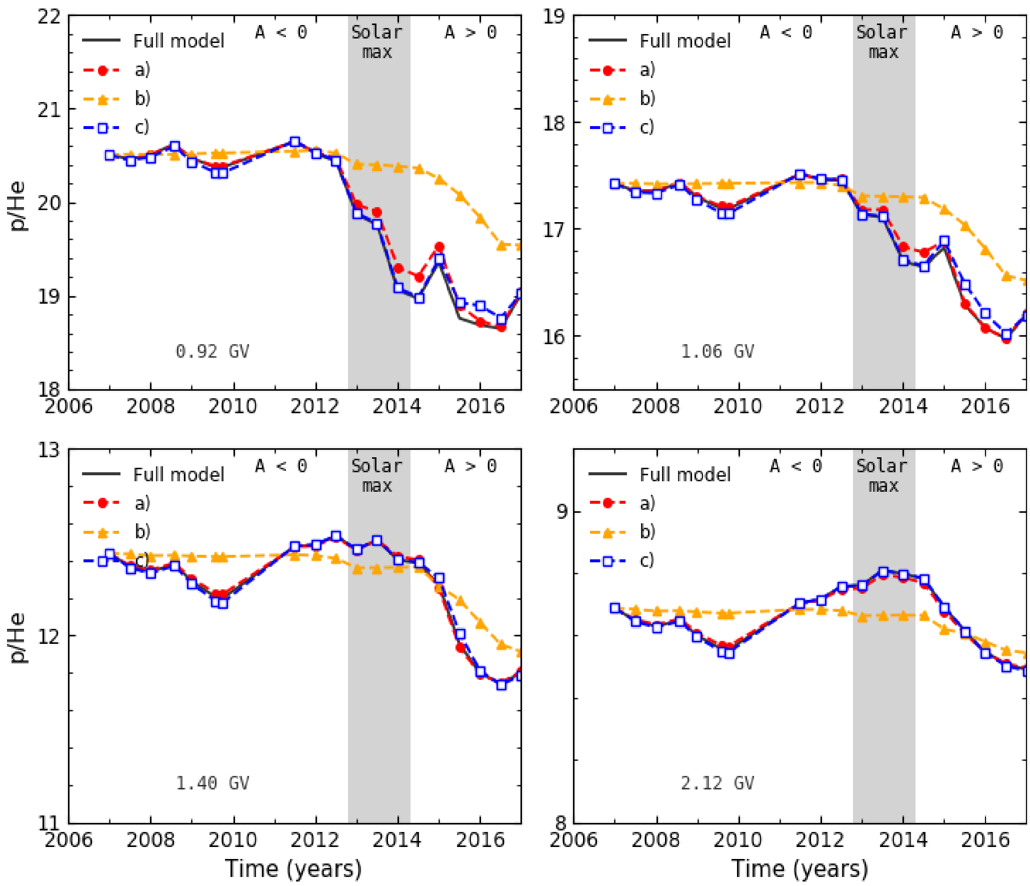

Figure 3: The computed p/He ratios for four rigidities between 0.92 GV and 2.12 GV, as a function of time at Earth corresponding to the four illustrative scenarios of MFPs and drift scale shown in Figures 1 and 2. Solutions obtained for the actual and complete time dependence shown in Figure 1 are indicated by solid black lines, whereas coloured lines indicated as a), b) and c) represent solutions obtained according to assumptions made for the three respective scenarios shown in Figure 2.

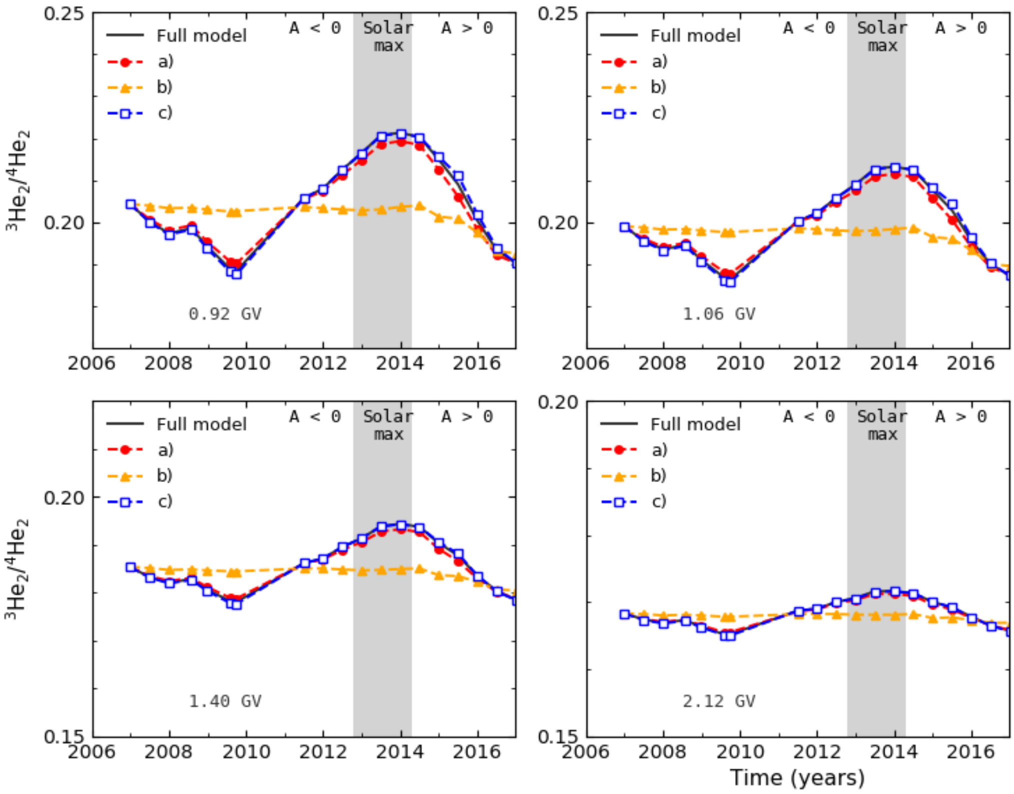

Figure 4: Similar to Figure 3 but now shown for $^3He_2/^4He_2$.

In Figure 3 the computed p/He ratios are shown at four rigidities from 2006 and 2017. Each of the four panels represents solutions obtained from the corresponding three scenarios of MFPs given in Figure 2 and the reference model with the complete time dependence shown in Figure 1. Here, the effects on the computed p/He of neglecting the time dependence of one of the individual diffusion coefficients are illustrated with emphasis on the resulting differences between these restrictive solutions for each of the three scenarios of MFPs (coloured lines) and the one using the complete model (black solid line). A comparison illustrates that the contribution of the time dependence of $K_{\perp r}$ is a dominant cause of the observed time variation. This differs for the two polarity epochs; at all rigidities shown, p/He remains relatively unaffected in the A < 0 cycle in response to the assumed constant value in $K_{\perp r}$, whereas in the A > 0 it decreases noticeably after solar maximum conditions, but not nearly as noteworthy as that obtained with the complete model. It follows that with the omission of the time dependence of $K_{\perp r}$, both in value and rigidity slopes, the model produces trends in p/He that is not observed below 3 GV at the Earth. As seen in all four panels, the time and rigidity changes in $K_{\parallel}$ and $K_{\perp \theta}$ produce some small effects but this clearly plays a less significant role in shaping the behaviour of the time trends in p/He.

Figure 4 is similar to Figure 3 but now the effects on $^3He_2/^4He_2$ are illustrated over the same period and for the same rigidity values. It is readily seen that when the time dependence of $K_{\perp r}$ is neglected the effect on this ratio is also significant, with the differences decreasing systematically with increasing rigidity, with no clear maximum in the restricted ratios associated with maximum solar activity. In contrast to the trends in p/He in Figure 3, these differences are also conspicuously less in the A > 0 cycle. Again, the time and rigidity changes in $K_{||}$ and $K_{\perp\theta}$ also produce some small effects but notably less in shaping the behaviour of the time trends in $^{3}He_2/^{4}He_2$.

3. Summary and conclusions

The computed results illustrate that the contribution of the time dependence of $K_{\perp r}$ is the dominant cause of the observed time variation in p/He and $^{3}He_2/^{4}He_2$, in particular during the A < 0 cycle. The effects of the time dependence of $K_{||}$ and $K_{\perp\theta}$ on the time dependences of p/He and $^{3}He_2/^{4}He_2$ ratios at rigidities below 3 GV are far less notable, although not to be ignored. Our results stipulate that neglecting the time dependence of $K_{\perp r}$, both in value and rigidity, from numerical models would produce time trends for both p/He and $^{3}He_2/^{4}He_2$ that are incongruent with observed trends at the Earth. It is to be emphasized that the differences between the time trends of these ratios observed by AMS [1] are not the cause of any fundamental difference between the solar modulation of galactic protons and Helium.

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