Solar modulation of Helium isotopes from minimum to maximum activity

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We apply our 3D numerical model to reproduce the observed features of $^3$He$_2$ to $^4$He$_2$ ratios.

To make meaningful comparison the modulation of both $^3$He$_2$ and $^4$He$_2$ is done using the same set of modulation parameters and diffusion coefficients as outlined in Ngobeni et al. (2020, 2021).

We illustrate and discuss differences that exist between $^3$He$_2$ and $^4$He$_2$ in their intensity profiles and ratios ($^3$He$_2$/^4$He$_2$) from 2011 till the beginning of 2017.
Transport equation for the modulation of cosmic rays in the heliosphere

Parker’s (1965) Transport Equation (TPE):

\[
\frac{\partial f}{\partial t} = \nabla \cdot [K \cdot \nabla f] - V \cdot \nabla f - \left\langle v_D \right\rangle \cdot \nabla f + \frac{1}{3} (\nabla \cdot V) \frac{\partial f}{\partial \ln p} + Q(r, p, t) \]

where:
- \( f(r, p, t) \) is the CR distribution function,
- \( K \) the diffusion tensor,
- \( V(r, \theta) = V(r, \theta)e_r \) the solar wind velocity vector and \( v_D \) is the averaged gradient and curvature drift velocity.

**Diffusion coefficients of interest:**

\[
K_\parallel = (K_\parallel_0 \beta \left( \frac{B_0}{B} \right) \left( \frac{P}{P_0} \right)^{\eta_1} D_\parallel(P), \quad K_{\perp r} = 0.02 \left( \frac{D_\perp}{D_\parallel} \right) K_\parallel, \quad K_{\perp \theta} = 0.02 F_{\perp \theta} \left( \frac{D_\perp}{D_\parallel} \right) K_\parallel = F_{\perp} K_{\perp r}
\]

with

\[
D_\parallel(P) = \left[ \left( \frac{P}{P_0} \right)^{\eta_3} + \left( \frac{P_k}{P_0} \right)^{\eta_3} \right]^{\eta_3} \left[ 1 + \left( \frac{P_k}{P_0} \right)^{\eta_3} \right]^{\eta_3 - \eta_3}
\]

and

\[
D_\perp(P) = \left[ \left( \frac{P}{P_0} \right)^{\eta_3} + \left( \frac{P_k}{P_0} \right)^{\eta_3} \right]^{\eta_3} \left[ 1 + \left( \frac{P_k}{P_0} \right)^{\eta_3} \right]^{\eta_3 - \eta_3}
\]
Assumed time-dependences of the DCs and their slopes

Just for illustrative purposes…
Differences are noted below 4 GV depending on mass-to-charge ratios (A/Z). For the MFPs the dependence on A/Z is eliminated.
Modulation of $^3\text{He}_2$ and $^4\text{He}_2$ compared to AMS-02 observations

- The model reproduces the spectral features of both $^3\text{He}_2$ and $^4\text{He}_2$ reasonably well.
The model can reproduce the single rigidity power law; and time independence of this ratio above 4 GV.
At lower rigidities the $^{3}\text{He}_2$/$^{4}\text{He}_2$ ratio reaches its peak during solar maximum conditions.
Summary and Conclusions

- It is found that both $^3\text{He}_2$ and $^4\text{He}_2$ observations can be reproduced reasonably well with the same set of modulation parameters and diffusion coefficients.

- The differences between $^3\text{He}_2$ and $^4\text{He}_2$ modulation effects are found to be the consequence of how the combined interplaying modulation mechanisms in the heliosphere affect the modulated spectra based on their A/Z and in particular on their respective VLIS's.

- At rigidities below 4 GV the ratio of $^3\text{He}_2$ to $^4\text{He}_2$ reaches its peak during solar maximum conditions.