Study galactic cosmic ray modulation with AMS-02 observation

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Introduction

Galactic Cosmic Rays (GCRs), which are charged, energetic particles originated outside the solar system, are accelerated by the energetic processes in the interstellar medium, show an isotropic distribution outside the heliopause. When entering the heliosphere, the flux of GCRs and it's spectrum shape are modulated by the disturbed solar wind with an embedded magnetic fields, which cause the so called solar modulation effect.

The accurate measurement of proton and helium by AMS-02 gives an unprecedented opportunity to study the difference of modulation between proton and helium, which is called the dependency of modulation on mass-to-charge ratio.

Model

The numerical model is based on the well known Parker transport equation:

$$\frac{\partial f}{\partial t} = -(\vec{V}_{sw} + \vec{V}_d) \cdot \nabla f + \nabla \cdot (\overset{\leftrightarrow}{K}_s \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \vec{V}_{sw}) \frac{\partial f}{\partial \ln p}. \qquad (1)$$

In this work, it is solved by means of time-backward stochastic differential equations (SDE).

Drift caused by large scale heliospheric magnetic field (HMF) can be expressed by:

$$\vec{V}_d = \nabla \times \left| K_A \frac{qR\beta}{3B} \frac{(R/R_0)^2}{1 + (R/R_0)^2} \frac{\vec{B}}{B} \right|, \qquad (2)$$

where K_A is a constant, range from 0 to 1. $R_0 = 0.9\,GV$. A widely used diffusion empirical formula is used in this work:

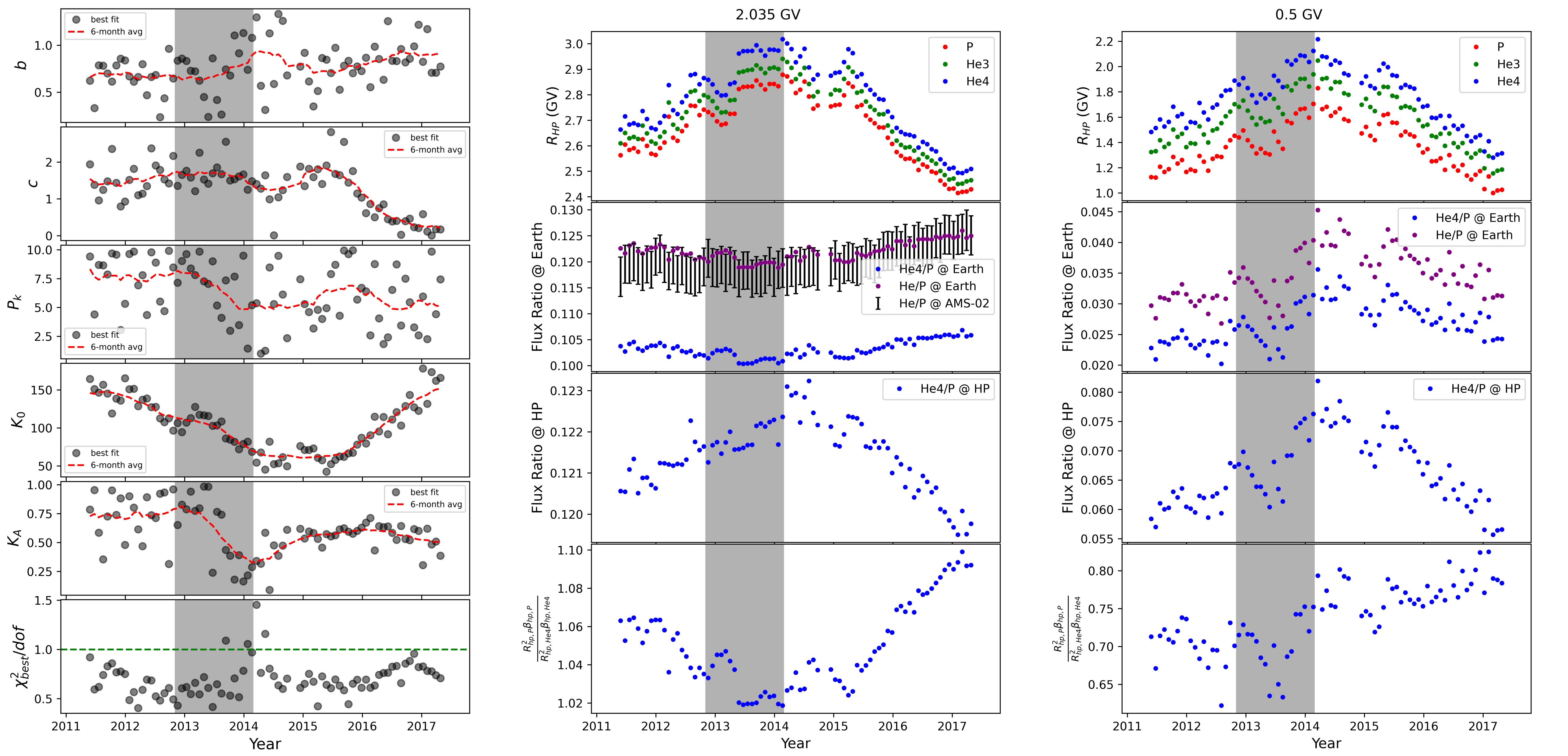
$$K_{\parallel} = K_0 \beta \left(\frac{B_{eq}}{B}\right) \left(\frac{R}{1GV}\right)^b \left(\frac{\left(\frac{R}{1GV}\right)^d + \left(\frac{R_k}{1GV}\right)^d}{1 + \left(\frac{R_k}{1GV}\right)^d}\right)^{\frac{c-b}{d}} \qquad (3)$$

where, K_0 is a constant in units of $10^{22}\ cm^2 s^{-1}$, the slope of rigidity dependence is b and c when the particle rigidity below and above than R_k, respectively. d determines the smoothness of the transition, and it is set equal to 3 for simplicity.

The local interstellar spectrum of proton and helium, which are the boundary condition of numerical model, are adopted from Corti et al. (2019). But the flux of He3 and He4 are recalculated based on He3/He4 observed by AMS-02.

The time varying coefficients K_A, K_0, b, c, R_k, are determined in each case using Markov Chain Monte Carlo method.

Result



(a) (b) (c)

Figure 1:left:The top five panels show the drift and diffusion coefficients from 2011 to 2017, the last panel shows the normalized χ^2 between model result and observation. middle and right:The effect of each part in Equation 5 on He/P at $R = 2.035\,GV$ and at $R = 0.5\,GV$

Drift and diffusion coefficients over time

In most cases, the χ^2/dof is less than 1, indicating a good agreement between model result and observations. The breakpoint (R_k) vary considerably from case to case, making it difficult to discern any clear time-dependent pattern. Slope of rigidity dependence b is smaller than c before 2016 making Equation 3 concave upward. After 2016, it become concave downward. The normalization of diffusion K_0 shows a clear time-dependent pattern: it decreases to the minimum value after solar polarity reversal (SPR), increases again until 2017. The drift coefficient K_A is more scattered before SPR than that after SPR. The mean value of K_A before 2013 is significantly larger than that after 2013, it decreases remarkably during SPR time interval and increases slightly after SPR.

He/P over time

In SDE method, the phase space distribution at Earth with momentum p is an average of its values outside the heliopause, which can be described by:

$$\frac{j(R)}{R^2\beta} = \frac{1}{N}\sum_{i=1}^{N} \frac{j_{hp}(R_i)}{R_i^2\beta_i} = \frac{j_{hp}(R_{hp})}{R_{hp}^2\beta_{hp}}. \qquad (4)$$

Then we define an effective rigidity R_{hp} which meets the requirement in Equation 4. So the ratio of helium to proton flux with the same rigidity, R, can be written as:

$$\frac{j_{He*}(R)}{j_P(R)} = \frac{j_{hp,He*}(R_{hp,He*})}{j_{hp,P}(R_{hp,P})} \frac{R^2_{hp,P}\beta_{hp,P}}{R^2_{hp,He*}\beta_{hp,He*}} \frac{\beta_{He*}}{\beta_P}, \qquad (5)$$

where $He*$ denotes the isotopes of helium (He3 or He4).

He/P over time

The right side of Equation 5 can be divided into 3 parts: $j_{hp,He*}/j_{hp,P}$ denotes the influence of LIS's difference between helium and proton, $(R^2_{hp,P}\beta_{hp,P})/(R^2_{hp,He*}\beta_{hp,He*})$ denotes the dependence of solar modulation process on A/Z, the last part is a constant and does not change over time.

Figure 1(b) shows the time variation of each part in Equation 5 for $R = 2.035\,GV$. It can be seen in the second panel that the He/P calculated by our model fit well with that measured by AMS-02. For the particle (P, He3 and He4) measured at the Earth with $R = 2.035\,GV$, the corresponding effective rigidity outside the heliopause (see in the first panel) show the same time variation: increases to the maximum value ($\sim 3.0\,GV$) at the end of SPR, and decreases again. The value of He3 is always larger than that of P, but smaller than that of He4. The third panel shows that the time variation of LIS's ratio is similar to that of R_{hp}. Though the LIS's ratio is implicitly dependent on A/Z through the difference of $R_{hp,P}$ and $R_{hp,He*}$, LIS's ratio has the similar variation trend under the same effective rigidity ($R_{hp,P}$ or $R_{hp,He*}$). The last panel show that the second part of Equation 5 have opposite variation trend with R_{hp} and have the similar variation trend with He/P near the Earth. The amplitude of variation in this part (9.8%) is larger than that of the first part (3.4%). Therefore, the time variation of He/P observed near the Earth with $R = 2.035\,GV$ is not originated from the P, He LIS's difference but from the solar modulation effect related to the mass-to-charge ratio.

Figure 1(c) is similar to Figure 1(b), but for particle with $R = 0.5GV$. In this case, R_{hp} is mainly less than $2GV$ and the variation amplitude is large enough, so the variation of first part in Equation 5 is larger than that of second part. The LIS's difference is the main factor leading to the variation of He/P near the Earth at $R = 0.5\,GV$.

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