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Comparison of Galactic Cosmic Ray Proton and Helium Spectra: Unraveling the Nuances of High - Energy Particle Acceleration

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Abstract: ***The flux of Galactic Cosmic Rays (GCRs) near Earth is modulated by solar wind and solar energetic particle events (SEPs), which are associated with solar flares and coronal mass ejections (CMEs). Scientists can gain insights into the acceleration and transport mechanisms of particles in the inner heliosphere through monitoring these variations. Because of their abundance and unique properties, helium nuclei (alpha particles) and protons play an important role in GCRs. The purpose of this scholarly article is to present a comprehensive comparative analysis of the spectra of helium and proton particles of galactic cosmic rays, shedding light on the underlying acceleration mechanisms and their implications for understanding the universe. A limited amount of literature exists about these important cosmic ray components. This report examines existing literature and employs sophisticated theoretical technique to elucidate the similarities, differences, and implications of helium and proton spectra in GCRs and our results show that*** **helium and proton spectra exhibit distinct properties and underlying processes.**

Keywords: Interstellar medium, cosmic rays, sun, solar wind, convection

1. Introduction

Since their discovery over a century ago, galactic cosmic rays have captivated scientists with their high energies and complex origins (Ihongo and Wang, 2016). While GCRs consist of a wide variety of particles, including electrons, positrons, and heavy nuclei, this study focuses on helium nuclei and protons. It is our aim to gain a better understanding of the acceleration mechanisms and the fundamental processes occurring in astrophysical sources by examining the spectra of these particles (Korsemeier and Cuoco, 2016). In our galaxy and beyond, cosmic rays are energetic particles. Major components are protons (hydrogen nuclei), helium nuclei (alpha particles), and traces of heavier elements. Supernova remnants, pulsars, and active galactic nuclei are thought to accelerate GCRs. Research continues on the acceleration mechanisms that produce the observed GCR spectra (Krizmanic 2002, Bandyopadhyay, 2019).

1.1 Helium and Proton Spectra

The spectra of helium and proton cosmic rays exhibit distinct features, providing insights into the acceleration and propagation processes. The helium spectrum, characterized by a smooth power - law distribution, spans a wide range of energies. Observations indicate that helium nuclei maintain a similar spectral index to protons up to energies of approximately 10^15 electron volts (eV), beyond which a slight steepening of the spectrum is observed. This steepening, known as the "knee" in the cosmic ray spectrum, is a phenomenon of great interest and still under investigation (Adriani, 2013).

1.2 Comparative Analysis of Spectral Features

1.2.1 Energy Dependence

The energy dependence of the helium and proton spectra plays a crucial role in understanding the acceleration mechanisms. At low energies, the spectra exhibit a power - law behavior, indicating a possible common acceleration mechanism. However, at higher energies, deviations are observed, suggesting additional acceleration processes or variations in source composition (Boezio, 2003).

1.1.2 Relative Abundance

Helium nuclei constitute a significant fraction of GCRs, comprising approximately 10 - 15% of the total cosmic ray flux. This abundance, combined with their unique properties, such as being heavier than protons, contributes to their distinct spectral characteristics. Comparing the helium and proton spectra allows us to explore the relative contributions of different astrophysical sources to GCR production (Boice, 2019).

1.1.3 Implications for Particle Acceleration Mechanisms

The comparison between helium and proton spectra provides valuable insights into the underlying acceleration processes. The similar spectral indices at lower energies suggest a common acceleration mechanism acting on both particle species. However, the steepening observed in the helium spectrum above the knee energy implies the existence of additional acceleration or propagation effects specific to helium nuclei.

2. Method

A theoretical approach based on the flux of galactic cosmic rays initially developed by (Potgieter2013; Moraal, 2011; Adagba 2021; Caballero - lopez 2012; Ihongo and Wang

2015) was used in this study. The flux as a function of kinetic energy is given in equation one (1)

$$j(T, \phi) = j\,(T^{\star})\left[\frac{T\,(T+2T_0)}{T(T+2T_0)+2\Phi(\sqrt{T\,(T+2T_0)}+\Phi^2}\right] \ldots\ldots\ldots\ldots\ldots (1)$$

where, $\Phi = \frac{Ze}{A}\phi$, $\phi = \frac{\mathbf{V}}{3k}(R - r)$ are 100 AU and 1AU respectively, Z and A are the atomic and mass numbers respectively**,** $k = 2.8 \times 10^{21}$, T is the kinetic energy (this model considers moderately high energies ranging from 0.2 to 100GeV), T_0 is the rest mass given by 0.9384GeV and $j(T^{\star})$ is the local interstellar spectrum assumed at the boundary of the heliosphere and is givenin equation two (2)

$$j(T^{*}) = b\beta\left(\frac{A}{Z}\sqrt{(T^{*})(T^{*}) + 2T_0}^{-a}\right) \ldots\ldots\ldots\ldots\ldots (2)$$

where (T^{*}) is the kinetic energy at the boundary of the heliosphere, $b = 1.82 \times 10^4$, $a = 2.788$ and $\beta = 1$.

The energy spectra of helium and proton were calculated separately, using equations 1 and the results are presented in figure 1 a – b. The simulation is implemented in MATLAB 2018.

2.1 Data Information

The solar wind (V) and $j(T^{*})$are inputs to the model. Solar wind data obtained from the ACE website: Srl. caltech. edu/ACE/ASC/rtsw. html for the month of May 2014 are used as input to the model, then the datafrom BESS 1998 for (T^{*})published in Sanuki et al. (2000) is usedto compute the boundary spectrum $j(T^{*})$for helium usingequation (2).

3. Result and Discussion

The results presented here are based on two types of computations. Computation based on the model and computation based on observational data. As a function of flux and kinetic energy, figure 1 (a and b) shows the time dependent force field solution for galactic cosmic ray for Helium (a) and Proton (b). In order to compare results based on this model with observational data, we calculated this as a function of flux and kinetic energy of the Helium and proton components. In the figure, we see that the black curve represents the local interstellar spectrum; this is an input spectrum that is modulated throughout the heliosphere by an assumed modulation boundary. Usually, this is calculated using satellite or experimental data since it has not yet been measured directly, although one of Voyager's primary aims is to measure the local interstellar spectrum. Solar wind speeds are represented by colour codes on the vertical axis. There is no doubt that the solar wind plays a crucial role in controlling the mechanisms of transport processes occurring continuously in the heliosphere. Solar wind convection, heliospheric diffusion, drift motion caused by magnetic field irregularities, and adiabatic energy changes are among the aforementioned processes, but the effect of solar wind remains the major modulator of cosmic ray intensity. Figure 1 (a and b) shows this effect where the flux bends over at low energies up to 18 GeV, for helium and 18 GeV for proton suggesting galactic cosmic ray flux modulation by the solar wind at energies up to 18 GeV and 18 GeV for helium and proton respectively (Boezio, 2003; Ihongo and Wang, 2015; Bartoli, 2015). As a result of the modulation effect, the colored spectra are called modulated spectra, while the black curve is called an unmodulated spectrum. As the solar wind speed increases, the spectra are observed to decrease, suggesting that each solar wind speed produces a slightly different spectrum. This is similar for both helium and proton. Possibly, this is due to the fact that the solar wind itself is not constant, and this unsteady nature may produce variations in galactic cosmic ray flux for both particles (Harwit, 2019; Ihongo and Wang, 2016). Above 18 GeV and 18 GeV for helium and protons respectively, coloured spectra harden and modulation seems to disappear. Perhaps this is because solar modulation is expected to be very small and perhaps negligible above these regions (Ihongo and Wang, 2016; Harwit 2019; Ihongo and Wang, 2016).

Figure 2 (a, b) shows a short time variation of the calculated flux for both helium and protons. An observation is made in Figure 1b that galactic cosmic ray flux variation is negatively correlated with solar wind variation. Based on other authors' findings, solar wind variation is negatively correlated with galactic cosmic ray variation (Ihongo and Wang, 2016; Khatun, 2019).

The abrupt decreases in flux may be related to high - speed solar wind streams (Khatun, 2019). suggest that high solar wind streams could reduce galactic cosmic ray flux. The flux variation appears to be primarily higher at low energies and lower at higher energies which may be due to variations in the solar wind speed as galactic cosmic ray flux is strongly modulated by the solar wind at lower energies, causing anisotropic variations in cosmic ray flux (Korsemeier and Cuocu, 2016).

Figure 2 (a, b) compares the short - time flux variation calculated. This shows that the model is consistent with observational data except for small discrepancies observed between 300 and 500 hours and between 650 and 720 hours for proton. According to the interpretation, cosmic ray intensity could be high when the solar wind speed stream is low while cosmic ray intensity might be low when the solar wind speed stream is high (Krizmanic, 2002; Tomassetti, 2019). That of helium has appeared differently and is consistent with other findings (Levich, 2018).

In Figure 3 (a, b) Calculated Helium and proton flux using the model red +, compared with data points from CAPRICE 1994 blue x, BESS 1993 green o, AMS 1998 red o, IMAX 1992 blue o, BESS 1998 cyan +, and CAPRICE 1998 magenta and figure 4 (a, b) which shows the model's actual hourly intensity variations without normalization. As time progresses, it is observed that the model flux increases, on average, at a rate of 0.1 percent per hour, while NM counts decrease, on average, at a rate of 0.01 percent per hour. There may be anisotropic variations in galactic cosmic ray intensity due to variations in solar wind speed (Ptuskin, 2013). This can be seen with a negative correlation between solar wind speed and galactic cosmic ray intensity.

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According to Figure 4 the main modulation parameter of the model is dependent on solar wind speed variations. It is observed that the wind speed is linearly related to solar wind speed, which means that the higher the solar wind speed, the stronger the wind. This thus, resulted in a negative correlation between galactic cosmic ray flux variation and solar wind speed variation, as reported bysimilar researchers (Roberts, 2017 andTomassetti, 2018).

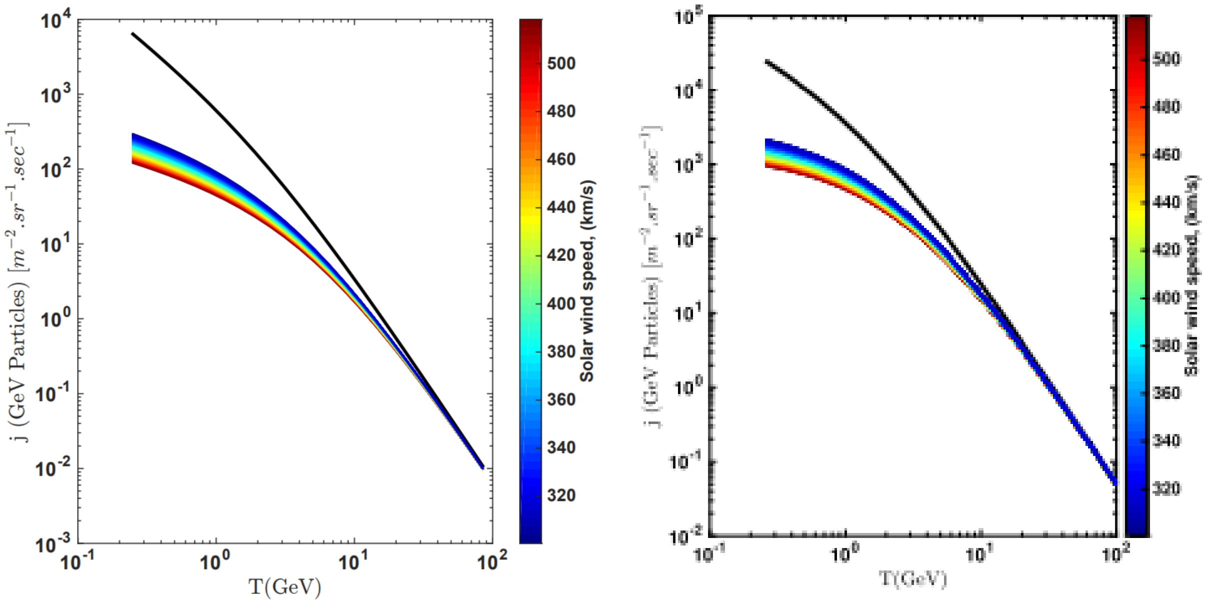

Figure 1 (a, b): galactic cosmic ray for Helium Spectra **Figure 1 (b):** galactic cosmic ray for Proton Spectra

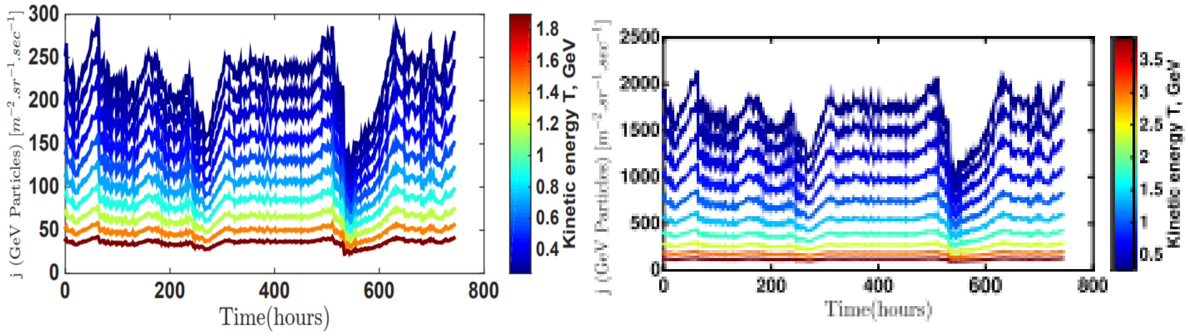

Figure 2 (a, b): The short time variation of flux for Helium (left) and proton (right)

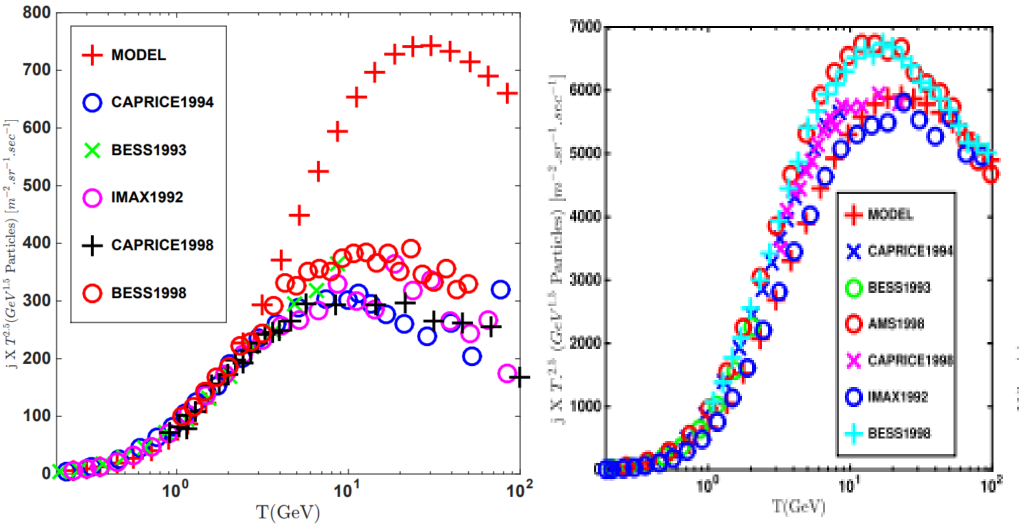

Figure 3 (a, b): Calculated Helium and proton flux using the model red +, compared with data points from CAPRICE 1994 blue x, BESS 1993 green o, AMS 1998 red o, IMAX 1992 blue o, BESS 1998 cyan +, and CAPRICE 1998 magenta

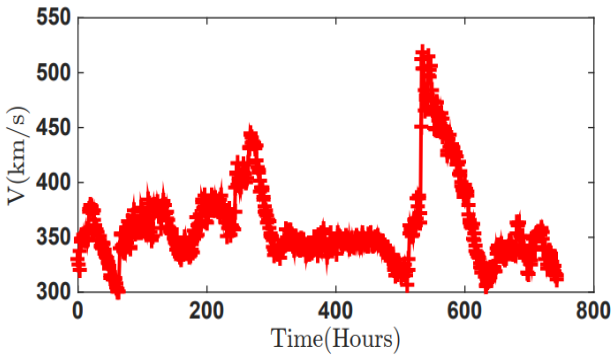

Figure 4: The solar wind profile

3.1 Observed Spectra

Helium and proton spectra are representations of differential fluxes or intensities of particles as a function of energy. Helium and proton cosmic ray spectra provide information about their abundance and energy distribution (Tomassetti, 2019).

3.2 Inference from this Study

It is evident from the comparison of the spectral shapes that the fluxes of helium and proton are energy - dependent. With increasing energy, the shapes may exhibit power - law decay, characterized by a negative slope. Changes in slope can indicate transitions or cut - off energies where flux decreases significantly. This is consistent with Tregillis (2002). Our results also reveal the relative intensities of these cosmic ray particles. Particles within a particular energy range are more abundant when flux values are higher. In addition to shedding light on the acceleration and propagation processes, the relative intensities provide insight into the composition and origin of cosmic rays in line with Tregillis (2002). However, significant differences are found between the helium and proton spectra. It is possible to observe differences in spectral shapes, peak energies, or relative intensities as a result of these differences. This could be attributed to the fact that Helium and proton particles exhibit unique characteristics and behaviours (Tomassetti, 2018). For example, Helium fluxes are lower compared to proton fluxes and the proton spectrum appear to be harder at higher energies.

4. Conclusion

A comparison of galactic cosmic ray spectra of helium and protons indicates that these particle species exhibit distinct properties and underlying processes, as revealed by their spectral shapes, relative intensities, peak energies, spectral indexes, and anisotropy patterns. As a result of this analysis, helium particles have steeper spectral slopes, higher relative intensities at lower energies, lower peak energies, and potentially different anisotropy patterns than protons, indicating that their acceleration mechanisms, propagation properties, and interactions with the interstellar medium differ. This will provide a deeper understanding of the astrophysical sources, the interstellar environment, and how cosmic rays accelerate and propagate.

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