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What Shapes the Energy Spectra of Galactic Cosmic Rays in the Local Interstellar Medium?

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The Voyager 1 (V1) energy spectra of cosmic-ray elements in the local interstellar medium (LISM) and models of interstellar propagation that fit these data, and which also fit the data taken at 1 AU at high energies [1], show a rollover from a power law at high energies to a broad peak at lower energies. We examine one of the GALPROP propagation models to investigate the roles of different physical processes in the rollover of the He spectrum at lower energies. We find that within the context of a GALPROP plain diffusion model, about two thirds of the rollover is due to ionization energy losses in the interstellar medium. The remaining one third is due to a combination of other effects, including most significantly the transformation from a rigidity source spectrum to the typical energy per nucleon spectrum presented by observers. Lesser in significance are changes in the rigidity dependence of the diffusion coefficient, changes in the injection spectrum, and nuclear interactions.

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1. Introduction

The energy spectra of galactic cosmic ray (GCR) nuclei and electrons have been measured in the local interstellar medium (LISM) for the first time by instruments on the Voyager 1 (V1) spacecraft [1]. The H and He energy spectra show intensity peaks in the 10-50 MeV/nuc energy range, having rolled over from steeply falling energy spectra at higher energies. It is generally thought that this rollover is due primarily to the effect of ionization energy losses in the interstellar medium (see, e.g., [2, 3]) and also perhaps due to the effect of a galactic wind [4]. In this paper we examine this question for the spectrum of He in the LISM using the estimated LISM spectrum from one of the GALPROP models that have been used to fit the not only the Voyager data, but also a variety of data near 1 AU as well [1].

The V1 GCR He energy spectrum in the LISM (from [1]) is shown in Figure 1, along with data from 1 AU at high energies. Two versions of the GALPROP [6] PD1 model are shown. The dotted line is the one published in [1]. We are using the latest version of GALPROP WebRun (version 54 and available at https://galprop.stanford.edu/webrun/) for this study. The WebRun version 54 of GALPROP is limited to source spectra with no more than one break in a power-law description. The source spectra in the GALPROP models in [1] all have two breaks in the rigidity power laws for He; however, the PD1 model He source spectrum can be approximated reasonably well with only one break. Hence, we chose that model for this investigation. The solid line in Figure 1 shows the result of using the modified source spectrum, which is shown in Figure 2. There are differences below ∼100 MeV/nuc between the two GALPROP versions in Figure 1 of up to ∼40%, but we deem these differences to be unimportant for the present study.

The dot-dashed line in the upper panel of Figure 1 is a power law with index -2.8, which is an extrapolation of the high-energy portion of the spectrum to low energies. The bottom panel shows that the rollover can be characterized by a change in slope of the power law of the GALPROP PD1 model spectrum from -2.8 at high energies to 0.2 at low energies, for an overall change in index of 3. The question addressed in this paper is: what causes that?

2. GALPROP parameters

In order to investigate the spectral rollover, we consider several effects: the transformation from the injection spectrum as a function of rigidity to one presented as a function of energy/nuc, the rigidity dependence of the injection spectrum, the rigidity dependence of the diffusion coefficient, and ionization energy losses. In this work we do not explore directly the effects of nuclear interactions on the observed energy spectrum nor do we consider the effects of a possible galactic wind or possible diffusive reacceleration.

2.1 Injection spectrum

As discussed earlier, the injection spectrum for the PD1 model for He nuclei used here is a broken power law in rigidity with one break:

$$\frac{dJ}{dR}(R) \propto (R/R_c)^{\gamma}, \quad \gamma = \begin{cases} \gamma_1 \text{ for } R < R_c \\ \gamma_2 \text{ for } R \geq R_c \end{cases} \tag{2.1}$$

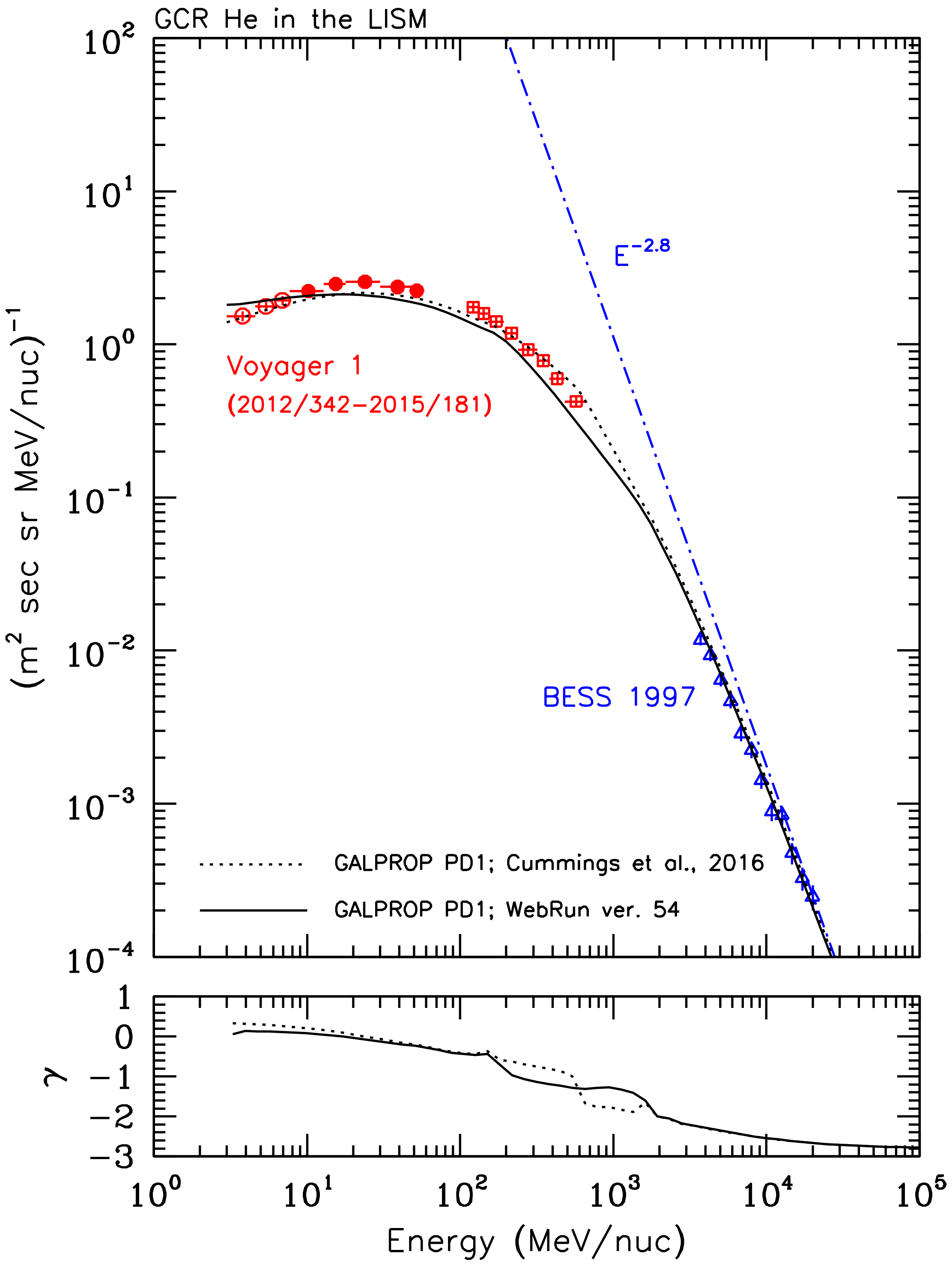

Figure 1: upper panel: Differential energy spectrum of He from V1 in the local interstellar medium (points below 200 MeV/nuc [1]), and the He spectrum at 1 AU from a 1997 BESS balloon flight [5] above 3 GeV/nuc where the solar modulation effects are not too severe. Also shown are estimated spectra in the LISM from the GALPROP PD1 model described in [1] (dotted line). The solid line represents essentially the same model but uses the publicly available WebRun version 54 of GALPROP with a slightly different source spectrum (see text for discussion). The dot-dashed line is a power law with index -2.8, shown for comparison. lower panel: Power-law index, γ, in $dJ/dE \propto E^{\gamma}$ for the GALPROP calculated energy spectra.

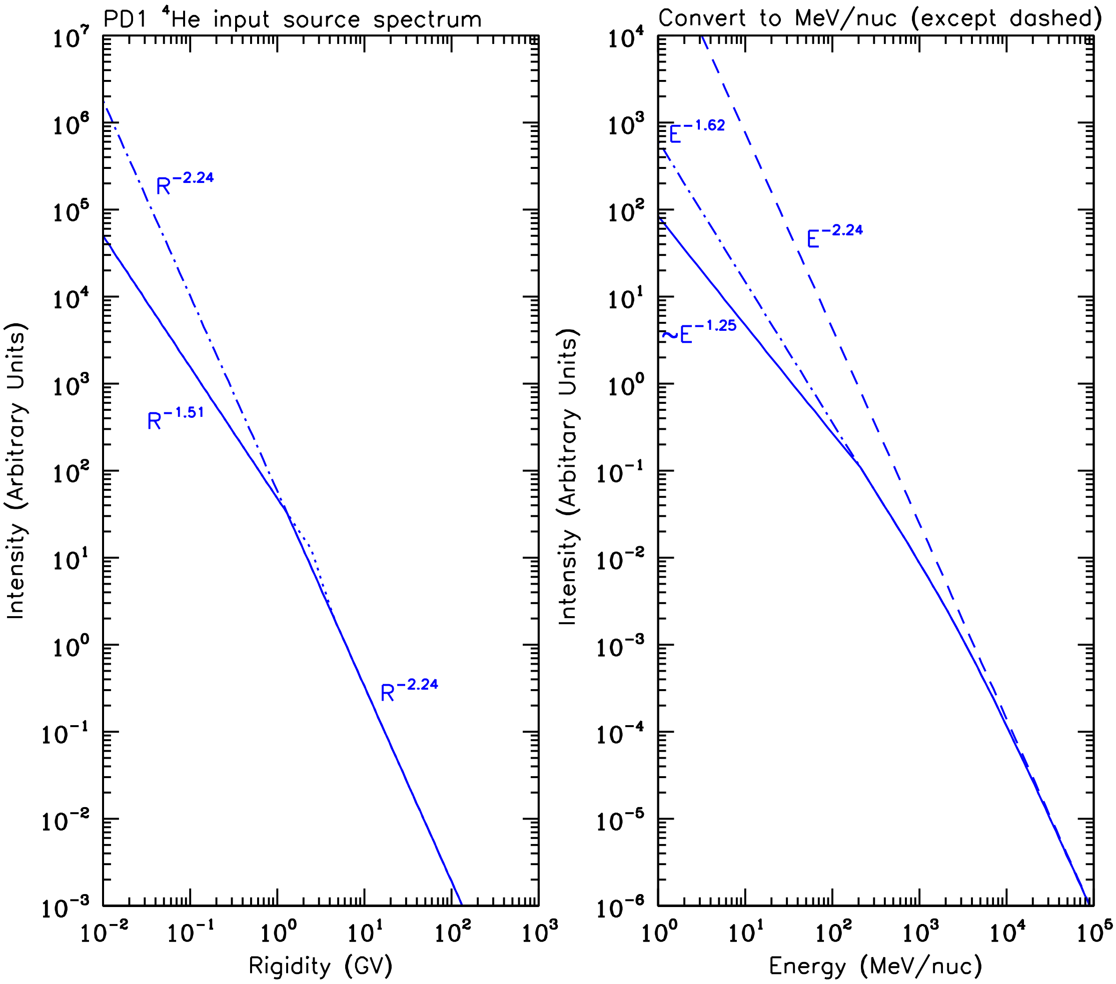

Figure 2: left panel: Input source spectrum for GALPROP model PD1 for He nuclei from the WebRun version 54 (solid line). The dotted-line segment is the portion of the source spectrum from [1] that differs from the one with one break in the power law used in this analysis. Also shown is a spectrum that is a single power law, which will be used to investigate the effect of changing the shape of the source spectrum. right panel: spectra in left panel converted to energy/nuc spectra. Also shown is a dashed line representing the high-energy power law extrapolated to low energies.

where R_c = 1.3 GV is the rigidity of the break, $\gamma_1 = -1.507$, and $\gamma_2 = -2.2431$

Even if the injection spectrum were a single power law in rigidity, there would be a natural rollover at low energies in a spectrum presented as dJ/dE, where E is in MeV/nuc, due to the conversion between a rigidity and energy/nuc spectrum. The conversion is given by: $\frac{dJ}{dE} = \frac{dJ}{dR}\frac{dR}{dE}$. The relationship between rigidity, R, and energy/nuc, E, is

$$R = \sqrt{(2MNE + N^2E^2)}/Q \tag{2.2}$$

where Q is the charge of the nucleus, M is the mass of the nucleus, and N is the number of nucleons. At high energies, $R \propto E$ and thus dR/dE is a constant and the rigidity and energy/nuc source spectra will have the same power-law index. At low energies, $R \propto \sqrt{E}$ and

$$\frac{dJ}{dE} \propto E^{(\gamma-1)/2} \tag{2.3}$$

where γ is the index of the power law describing the rigidity dependent source spectrum: $dJ/dR \propto R^{\gamma}$.

The conversion between rigidity and energy/nuc source spectra is depicted in Figure 2. If the injection spectrum were to be a single power-law with index -2.24, the rolled-over source spectrum would have an index of -1.62, for an index change of 0.62 before any propagation effects are considered.

2.2 Diffusion coefficient

The spatial diffusion coefficient in the GALPROP PD1 model in [1] is given by a broken power law in rigidity:

$$D(R) \propto \beta \left(R/R_d\right)^{\alpha}, \qquad \alpha = \begin{cases} \alpha_1 \text{ for } R < R_d \\ \alpha_2 \text{ for } R \geq R_d \end{cases} \tag{2.4}$$
$$D(R_0) = D_0, \qquad R_0 = 40 \text{ GV},$$

where R_d is the rigidity of the break (4.886 GV), R_0 is the normalization rigidity (40 GV), $D_0 = 1.22 \times 10^{29}\text{cm}^2\text{s}^{-1}$, and $\beta \equiv v/c$. (Please note that there is an error in [1] such that the normalization rigidity R_0 is really 40 GV, not the 10 GV listed.) The values of α_1 and α_2 are -0.631 and 0.570, respectively.

Once the high-rigidity index of the source spectrum is fixed at -2.24, the high-rigidity index of the diffusion coefficient is constrained to be ~0.57 in order to match the high-energy portion of the power law of the observed spectrum, since the observed spectrum at high energies should be steeper than the injection spectrum by the index of the diffusion coefficient at high energies (see, e.g., [7]). As shown in Figure 1, the index at high energies from the model is -2.8, as expected from the GALPROP parameters.

The diffusion coefficient used in the GALPROP PD1 model in [1] is shown in Figure 3.

2.3 Ionization energy losses

There is a parameter in GALPROP that can be set to turn on or off momentum losses, which is essentially equivalent to turning on or off the ionization energy losses in our case, since there is no galactic wind in any of the GALPROP models in [1] and we are not considering diffusive reacceleration.

3. Results

The methodology employed is to first consider a GALPROP PD1 model that is reasonably simple with respect to key parameters: no breaks in the power-law prescriptions of the injection spectrum or the diffusion coefficient and with ionization losses turned off. Even in this simple case,

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a change would be expected in the observed spectrum from high energies to low energies due to the conversion from rigidity to energy/nuc space and also due to nuclear interactions and the particular specification of the diffusion coefficient. The result of this model is shown as the curve labeled Model 1 in Figure 4. There appears to be a deficit in the spectrum between ∼20 to 100 MeV/nuc, which may be due to the resonance in the interaction cross-section in that energy range (see Figure 1 in [8]). At the low energies of interest below ∼10 MeV/nuc, where the power-law index for the observations is ∼0.2, the index in the Model 1 spectrum is ∼-1.9, the value expected from the conversion from a spectrum expressed in rigidity units to one in energy/nuc units. The total slope change from -2.8 at high energies resulting from using Model 1 is ∼0.9.

The next step is to turn ionization energy losses on and the result is shown by the curve labeled Model 2 in Figure 4. The resulting spectral slope in the region of interest is near zero. Thus the ionization energy losses do serve to flatten out the energy spectrum considerably, accounting for a slope change of 1.9 units or nearly 2/3 of the of the observed change in slope from the power law at high energies.

Models 3 and 4, which add the breaks in the injection spectrum and in the diffusion coefficient, respectively, are seen to fine tune the slope below ∼10 MeV/nuc to the observed value of ∼0.2 and also to lower the intensity at low energies by a factor of ∼3 to match the observations.

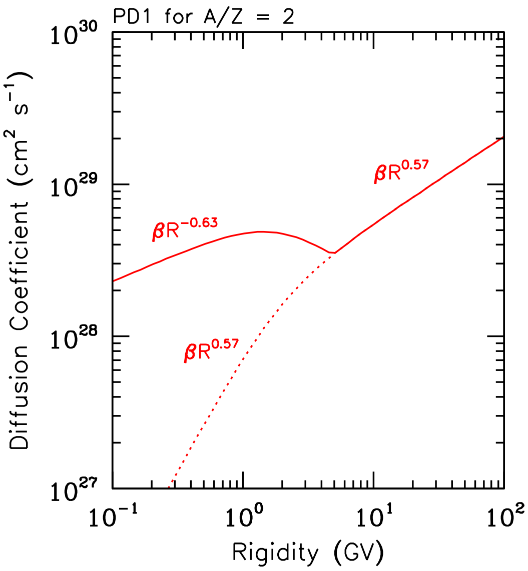

Figure 3: Diffusion coefficient for GALPROP PD1 model from [1] (solid line). The dotted line represents a diffusion coefficient that is a single power law in rigidity, which is used to investigate the effect on the observed spectrum of changing the shape of the diffusion coefficient.

4. Summary

The goal of this study was to understand why the observed energy spectrum of He in the LISM begins at high energies with a power law with index -2.8 and rolls over to a power law with index ∼0.2 at low energies. Only the GALPROP PD1 model described in [1] with a slightly modified source spectrum was used in the investigation. We find that, under the contraints of this model, about 2/3 of the slope change can be atributed to ionization energy losses in the interstellar medium. A big part of the remainder is due to the conversion of an injection spectrum specified as a power law in rigidity to a spectrum that is prescribed in terms of energy/nuc. Lesser contributions to the slope change are due to the diffusion coefficient and the change of its slope, nuclear interactions, and by changing the slope of the injection spectrum. We note that other models might use a different type of injection spectrum and may include effects not investigated here, such as diffusive reacceleration, or a galactic wind, and might reach somewhat different conclusions

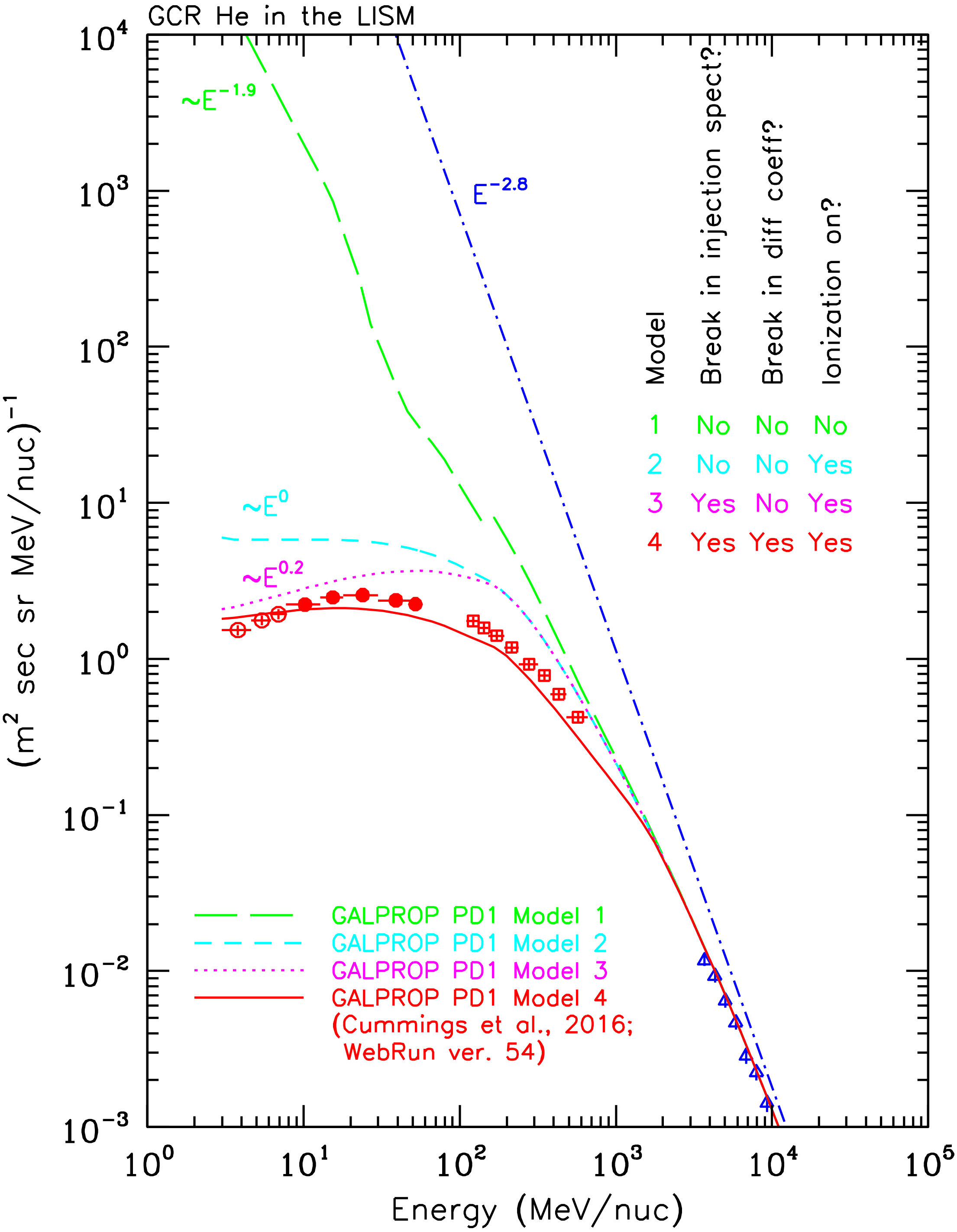

Figure 4: Same as Figure 1 with the addition of results from model runs as described in the text.

in detail. However, it seems clear that ionization energy losses will account for a big part of the rollover in any model considered.

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