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# Cosmic-Ray Energy Spectra and Time Variations in the Local Interstellar Medium: Constraints and Uncertainties

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**Abstract** The spectra of galactic cosmic rays that are observed inside the heliosphere result from the interaction of the spectra present in the local interstellar medium with the structured but turbulent magnetic field carried by the solar wind. Observational tests of solar modulation theory depend on comparisons between spectra inside and outside the heliosphere. Our knowledge of the local interstellar spectra are indirect, using extrapolations of interplanetary spectra measured at high energies where solar modulation effects are minimal and modeling of the physical processes that occur during particle acceleration and transport in the interstellar medium. The resulting estimates of the interstellar spectra can also be checked against observations of the effects that cosmic rays have on the chemistry of the interstellar medium and on the production of the diffuse galactic gamma-ray background. I review the present understanding of the local galactic cosmic-ray spectra, emphasizing the constraints set by observations and the uncertainties that remain.

**Keywords** Cosmic rays · Interstellar medium · Solar modulation

## 1 Introduction

At energies above a few tens of GeV, cosmic rays measured near Earth show negligible time variation, at least over the time scale that these particles have been observed. However at energies $\lesssim$1 GeV, cosmic-ray intensities observed near Earth undergo significant variations that correlate with the 22-year magnetic cycle of the Sun, 11-year sunspot cycle, or shorter term manifestations of solar activity (e.g., Forbush decreases following the passage of coronal mass ejections). Understanding these solar influences on cosmic rays in the heliosphere depends on comparing spectra observed in the interplanetary medium with those thought to be present outside the heliosphere.

The local interstellar spectra of the various cosmic-ray species (p, e, heavy ions, $\overline{\mathrm{p}}$, $\mathrm{e}^+$) reflect the physical processes involved in synthesizing the particles, in accelerating them to

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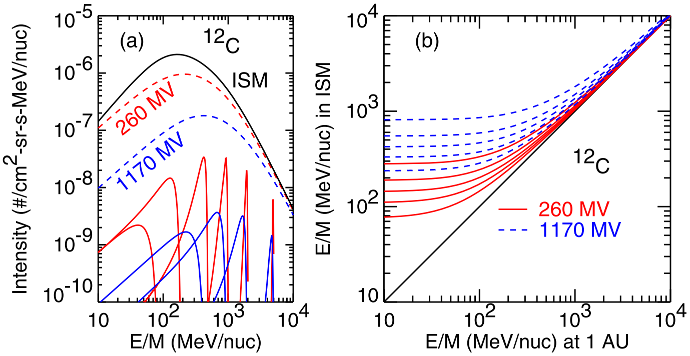

**Fig. 1** Calculated effects of solar modulation on the $^{12}$C energy spectrum at solar minimum (modulation parameter $\phi = 260\,\mathrm{MV}$, *red*) and solar maximum ($\phi = 1170\,\mathrm{MV}$, *blue*). In the approximation that solar modulation is spherically symmetric, the modulation parameter (Gleeson and Axford 1968) depends on the particle rigidity ($R$) and velocity ($\beta c$), the solar wind speed ($V_{\mathrm{SW}}$), the interplanetary diffusion coefficient ($\kappa$), and the heliocentric radius of the presumed modulation boundary ($r = D$) as $\phi \equiv (R/3) \cdot \int_{1\,\mathrm{AU}}^{D} [V_{\mathrm{SW}}(r)\,\beta/\kappa(r, R)]dr$. Panel **a**: estimated ISM spectrum using analytic approximation given by George et al. (2009) and spectra modulated to 1 AU (*dashed curves*). *Lower solid curves* show spectra at 1 AU obtained by modulating nearly monoenergetic (1% energy width) portions of the $^{12}$C spectrum at ISM energies (right to left) of 5000, 2000, 1000, 500, 200, and 100 MeV/nucleon (see also Labrador and Mewaldt 1997). Panel **b**: 5th, 25th, 50th, 75th, and 95th percentiles of the ISM energy distribution that contributes to the particles observed at a given energy at 1 AU, assuming the ISM spectrum shown in panel **a**

high energies, and in transporting them through the interstellar medium (ISM). Calculations based on the physics of the processes thought to be involved and on a number of empirical parameters inferred from cosmic-ray observations can be used to make estimates of the local interstellar spectra at energies where solar modulation has moderate effects on the observed spectra. At the lowest interstellar energies, below several hundred MeV (or MeV/nucleon for heavy nuclei), the particles do not penetrate deep into the heliosphere and very little is known from direct cosmic-ray observations. Figure 1 illustrates this point for the case of cosmic-ray $^{12}$C. In the left panel an estimated local interstellar spectrum (George et al. 2009) is shown together with the results of a spherically-symmetric modulation calculation (Fisk 1971) using parameters appropriate to solar minimum and solar maximum (red and blue, respectively). Also shown are the contributions to the 1 AU spectra due to narrow portions of the interstellar spectrum. The reduction in intensity and the reduction and spreading in energy below $\sim$1000 MeV/nucleon is significant, particularly at solar maximum. The right-hand panel shows percentiles of the distribution of interstellar energies that contribute to a given energy observed at 1 AU in the case of the spectra shown in the left panel. Most of the particles observed below a few hundred MeV/nucleon had significantly higher energies in the local ISM.

In the following sections we separately consider three cases: heavy elements ($Z \geq 2$), protons and antiprotons, and electrons and positrons.

## 2 Heavy Elements

For heavy cosmic-ray nuclei the effects of the interstellar propagation of cosmic rays (reviewed by Strong et al. 2007) can be written in terms of a continuity equation taking into account the processes that produce and destroy cosmic rays and transport them in space and in energy. Expressing rates for production and loss processes in terms of mean free paths (denoted $\Lambda$), a simplified version the equation for the steady-state interstellar intensity $\varphi_i$ of a nuclide of atomic number $Z_i$ and mass $M_i$ appears as:

$$0 = q_i + \sum_j \frac{\varphi_j}{\Lambda_{ji}} - \frac{\varphi_i}{\Lambda_i} - \frac{\varphi_i}{\Lambda_{\text{esc}}} + \frac{\partial(w_i \varphi_i)}{\partial \epsilon}, \tag{1}$$

where $\epsilon$ denotes energy per nucleon and $w_i$ is the specific ionization per nucleon (Meneguzzi et al. 1971). The terms represent: the initial acceleration of source material ($q_i$); production as the result of collisions between heavier cosmic rays and interstellar gas nuclei ($\sum_j \varphi_j/\Lambda_{ji}$); destruction by such collisions ($\varphi_i/\Lambda_i$); escape from the Galaxy ($\varphi_i/\Lambda_{\text{esc}}$), which serves as a short hand for the spatial transport effects of interstellar diffusion and convection; and energy changes due to ionization energy loss ($\partial(w_i\varphi_i)/\partial\epsilon$). Additional processes, which need to be taken into account in particular cases, include: loss and production by radioactive decay of unstable nuclides (e.g., $^{10}$Be decaying to produce $^{10}$B); attachment and loss of atomic electrons by the cosmic-ray nuclei, which can alter the decay rates of nuclides that decay by capturing an orbital electron; and stochastic "reacceleration" as cosmic-rays interact with the magnetic-field turbulence in the interstellar plasma. A distinction is made between "primary" species ($q_i \gg \sum_j \varphi_j/\Lambda_{ji}$) that are accelerated in the Galaxy and "secondary" cosmic rays ($q_i \ll \sum_j \varphi_j/\Lambda_{ji}$) dominantly produced as reaction products in collisions of heavier species, which represent the two extremes of a continuum of mixtures of these two classes of particles.

The GALPROP model (Strong et al. 2004, and references therein), which incorporates all of the aforementioned effects including spatial transport and takes into account a variety of constraints from astronomical and cosmic-ray observations, is widely used for calculating the effects of the interstellar propagation of cosmic rays. The simplified "leaky-box" formulation of the propagation equation given in (1) will suffice for a general discussion of the essential features of cosmic-ray propagation.

### 2.1 Heavy Elements at High Energies

Figure 1 shows that at energies above a few tens of GeV/nucleon cosmic-ray energy spectra are largely unaffected by solar modulation. This energy dependence of the modulation is caused by the fall off of the power spectrum of the interplanetary magnetic field turbulence with increasing wave length since the particle diffusion is dominated by resonant scattering on magnetic-field fluctuations having wavelength comparable to the particle's gyroradius (Jokipii 1971). Thus spectra above a few tens of GeV/nucleon can be used as constraints on models of the interstellar propagation of cosmic rays without requiring a detailed understanding of solar modulation. Furthermore, interstellar propagation of cosmic-ray nuclei is particularly simple at energies above a few tens of GeV/nucleon. Not only are the calculations well constrained by the essentially unmodulated spectra measured at 1 AU, but other terms in the propagation equation are particularly simple at these high energies: ionization energy loss becomes negligible and fragmentation cross sections become energy independent.

Measured energy spectra for primary cosmic-ray nuclei are, to a good approximation, power laws in the energy range from $\sim 10^4$ to at least $10^6$ MeV/nucleon. For primary elements such as H, He, C, O, Ne, Mg, Si, and Fe, $\varphi \propto \epsilon^\gamma$ with $\gamma \simeq -2.7 \pm 0.1$ (Ave et al. 2009, and references therein). Spectra for purely secondary elements fall more steeply, causing primary-to-secondary ratios such as B/C or (Sc + Ti + V)/Fe to fall with increasing energy $\propto \epsilon^\alpha$ with $\alpha \simeq -0.6$ (Strong et al. 2007; Tomassetti et al. 2009, and references therein). For elements consisting of a mix of primary and secondary material the primary fraction increases with increasing energy. At sufficiently high energies $\Lambda_{\text{esc}}$ becomes small compared to $\Lambda_i$ in (1) and the energy change term becomes negligible, so the energy dependence of a secondary-to-primary ratio directly reflects the energy dependence of $\Lambda_{\text{esc}}$, from which one infers that $\Lambda_{\text{esc}}$ falls approximately as $\epsilon^{-0.6}$. The equilibrium spectrum for a primary element is softened relative to the source spectrum by this energy dependence of $\Lambda_{\text{esc}}$, so at high energies the source spectra go approximately as $q_i \propto \epsilon^{-2.3}$ (Ave et al. 2009).

### 2.2 Heavy Elements at Intermediate Energies

Since at high energies the physical quantities energy, momentum, rigidity (for fixed $M/Z$), and functions of velocity times these quantities are all proportional, the appropriate variables for parameterizing the energy dependences of $q_i$ and $\Lambda_{\text{esc}}$ are not uniquely determined. To extend the high-energy results down into the energy range below 1 GeV/nucleon the source spectra must be extrapolated using some assumption about which is the relevant variable. Diffusive shock acceleration theory predicts energy spectra that are power laws in momentum with a spectral index $\leq -2$ that depends on shock strength (e.g., Blandford and Ostriker 1978). Thus a number of calculations have been done assuming that the high-energy power law can be extrapolated in momentum down to the lowest energies.

The energy dependence of $\Lambda_{\text{esc}}$ can be derived from secondary-to-primary ratios even in the intermediate energy range by taking into account all the terms in (1). These calculations do depend weakly on a solar modulation calculation to convert from a secondary-to-primary ratio measured at 1 AU to the corresponding ratio in the ISM, but this should not be a major source of uncertainty when considering abundance ratios between elements with similar $M/Z$ at energies above ~500 MeV/nucleon. The energy dependence inferred for $\Lambda_{\text{esc}}$ is not a simple extrapolation of the high-energy behavior; $\Lambda_{\text{esc}}$ needs to decrease toward low energies to account for the low-energy decrease of B/C and other secondary-to-primary ratios (Davis et al. 2000; George et al. 2009; Strong et al. 2007, and references therein). The physical origin of the low-energy decrease in $\Lambda_{\text{esc}}$ remains unclear. Suggested explanations include: convection out of the Galaxy in a galactic wind; "reacceleration" during propagation due to interaction with waves in the ISM, possibly generated by streaming of cosmic-ray protons; and a low-energy contribution from a relatively local source of cosmic rays that have not penetrated much interstellar material and thus are deficient in secondary elements. Strong et al. (2007) have reviewed these alternatives and provided references to the original papers.

Measurements of the energy spectra of radioactive cosmic-ray isotopes that can decay only by orbital electron capture (ec) are also useful for providing constraints on models of solar modulation. Since cosmic-ray nuclei are readily stripped of all of their orbital electrons by Coulomb collisions in the interstellar medium, such ec radionuclides are effectively stable in the cosmic rays. Thus, for example, $^{7}$Be is observed in cosmic rays in the abundance one would expect from fragmentation of heavier nuclei, in spite of the fact that its laboratory halflife for ec decay is 0.3 yr as compared to the typical cosmic-ray residence time in the Galaxy of ~15 Myr. At several hundred MeV/nucleon, some higher-$Z$ ec elements have a non-negligible probability of attaching an orbital electron from matter in the interstellar medium and retaining it long enough that ec decays can occur. Since the electron attachment cross section has a relatively strong energy dependence, this should lead to a calculable feature in the local interstellar spectra of these ec nuclides and in the daughter products to which they decay. This feature can serve as an energy marker that should appear at a lower energy in the spectra observed at 1 AU and provide a measure of the amount of energy loss due to solar modulation. Applying this type of analysis to the ec nuclides $^{49}$V and $^{51}$Cr, Niebur et al. (2003) concluded that the energy loss due to solar modulation was ~200 to 300 MeV/nucleon greater at solar maximum (2000 Feb 24 to 2003 Jan 5) than solar minimum (1997 Aug 28 to 1999 Aug 17).

## 3 Protons and Antiprotons

Protons, which constitute ~90% of the cosmic rays, undergo the same transport processes as heavy nuclei. However the only readily distinguishable secondary products of their collisions with interstellar matter are antiprotons. The production of proton–antiproton pairs has a threshold energy ~10 GeV in the laboratory frame. At this energy the interstellar proton spectrum can be derived by demodulating the spectrum measured at 1 AU with only minor uncertainty. Combining this ISM spectrum with the known production cross sections and kinematics, the interstellar $\overline{\mathrm{p}}$ spectrum can reliably be calculated even for low energies (Simon et al. 1998). By contrast, the proton spectrum has the same large uncertainties in the low-energy region as do the spectra of heavy elements, as discussed above. Thus the comparison of 1 AU measurements of the $\overline{\mathrm{p}}$ spectrum with the calculated local interstellar medium spectrum is particularly useful for probing solar modulation. The energy dependence of the $\overline{\mathrm{p}}/\mathrm{p}$ ratio, which is frequently reported from observational investigations, is less useful because it is subject to the large uncertainty in the interstellar proton intensity (Labrador and Mewaldt 1997).

Presently available antiproton data (Adriani et al. 2010), which extend from ~100 to $\sim 10^5$ MeV, are generally consistent with all of the $\overline{\mathrm{p}}$'s being produced as secondaries in models of the same type required to explain the cosmic-ray heavy nuclei (see, however, Moskalenko et al. 2002).

Modulation effects on proton and antiproton spectra are expected to differ somewhat due to the charge-sign dependence introduced by gradient and curvature drifts (Jokipii et al. 1977).

## 4 Electrons and Positrons

In recent years the spectrum of cosmic-ray electrons (by which I mean both negatrons, $e^-$, and positrons, $e^+$) has been precisely measured over a broad energy range at 1 AU (Boezio et al. 2000; Torii et al. 2001, 2008; DuVernois 2001; Aguilar et al. 2002; Ackermann et al. 2010; Aharonian 2008) and its positron fraction has been determined up to ~100 GeV (Boezio et al. 2000; DuVernois 2001; Aguilar et al. 2002; Adriani et al. 2009). In addition, measurements from Voyager have determined the low-energy ($\lesssim$100 MeV) electron spectrum beyond the heliospheric termination shock (Webber and Higbie 2008).

The primary difference between the galactic propagation of electrons and that of protons and heavy nuclei is in the energy loss mechanisms that are relevant (Moskalenko and Strong 1998). At cosmic-ray energies, electrons are relativistic and ionization energy loss is insignificant. However at energies above a GeV these light particles can lose energy by synchrotron emission in the galactic magnetic fields and by bremsstrahlung as they undergo scattering by collisions in the interstellar gas. The energy loss rate grows as the square of the electron energy and, at energies approaching a TeV, causes a steep roll-off of the electron spectrum (Kobayashi et al. 2004; Aharonian 2008) as the distance these particles can propagate becomes comparable to the distance to the nearest sources. Indications of an unexpected hardening of the electron spectrum above 100 GeV (Chang et al. 2008; Torii et al. 2008; Aharonian 2008, 2009; Ackermann et al. 2010) have generated a great deal of excitement and copious attempts at explanations in terms of new physics or modifications of conventional propagation models, but the size and reality of the effect remains to be firmly established. In a similar way, the report of an increase in the positron fraction above ~10 GeV (Adriani et al. 2009, and references therein), which also waits confirmation, prompted both exotic and conventional explanations. One of the latter (Roberts 2011) is relevant to the subject of solar modulation in that it suggests the positron excess is due to focusing of particles with gyroradii larger than the north–south extent of the heliospheric current sheet and predicts a solar cycle variation of the $e^+/(e^- + e^+)$ value at 1 AU even at these high energies.

At lower energies the synchrotron and bremsstrahlung emission from cosmic-ray electrons dominate the galactic radio spectrum coming from the regions of the galactic poles where other radio sources are sparse (Webber and Higbie 2008, and references therein). This radio emission provides a rather direct measure of the interstellar electrum spectrum that can be compared with electron observations at 1 AU and by Voyager in the outer heliosphere to investigate solar modulation of electrons. Using this technique, Webber and Higbie (2008) concluded that at energies below ~100 MeV the electron intensity at ~105 AU from the Sun was lower than the local interstellar intensity by a factor ~5–10. This comparison between the electron spectrum measured by Voyager and that inferred for the interstellar medium also confirms the result obtained from analysis of the energy dependence of elemental secondary-to-primary ratios that the escape mean free path must decrease at low rigidities, corresponding to an increase in the interstellar diffusion coefficient.

## 5 Constraints from Astronomical Observations

All of the constraints on the local interstellar spectra of cosmic rays considered above depended on cosmic-ray measurements made inside the heliosphere, mainly at 1 AU, in conjunction with various degrees of modeling of interstellar propagation. Another class of constraints can be obtained from astronomical observations that are sensitive to the interactions cosmic rays experience with interstellar matter.

### 5.1 Gamma-Ray Production

High-energy collisions between cosmic-ray nuclei and interstellar gas atoms, primarily $p + H$, can produce neutral pions, which subsequently decay to produce two or three gamma-rays. Thus the gamma-ray spectrum can serve as a probe of the interstellar cosmic-ray spectrum responsible for these interactions. The 135 MeV center of mass energy required to produce a $\pi^0$ sets a relatively high threshold for this reaction. As shown in Fig. 2a, the $\pi^0$ production cross section is a rising function of proton momentum starting at ~1 GeV/c, and thus the gamma-ray production depends on the high-energy portion of the interstellar proton spectrum, which is fairly well known. Although $p + H$ reactions dominate the gamma-ray production, there are also contributions due to heavier elements in the cosmic-ray flux and in the interstellar medium. Since accurate determinations of the numerous heavy-ion cross sections have not been available, the standard approach has been to calculate the $p + H$ contribution and apply a correction factor that is found to have a value ~1.8–2, with a weak energy dependence (Mori 2009). This heavy-ion correction is a significant source of uncertainty in the gamma-ray yield calculation. Gamma-rays can also be produced by cosmic-ray

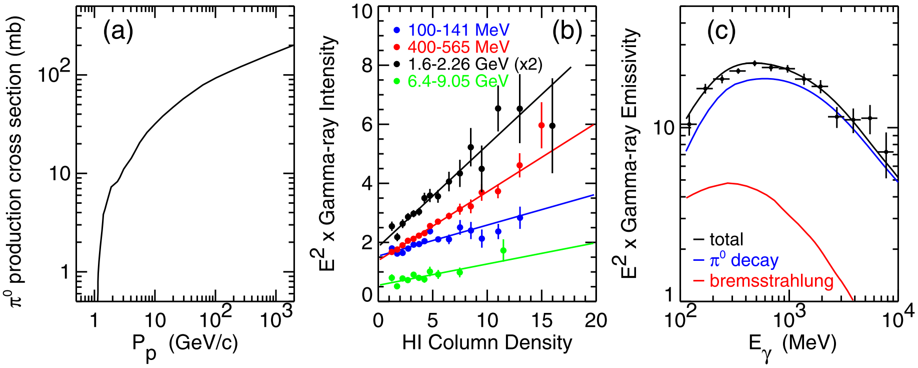

**Fig. 2** Panel **a**: dependence of the inclusive cross section for $\pi^0$ production on the momentum of the cosmic-ray proton colliding with interstellar matter. Panel **b**: correlation between gamma-ray intensity $\times E^2$ (in units of $\mathrm{MeV}^2\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{MeV}^{-1}$) and the H I column density along various lines of sight. Intensities for the 1.6–2.26 GeV energy range have been multiplied by 2 to avoid overlap with the other data. Panel **c**: Comparison of differential gamma-ray emissivity $\times E^2$ (units of $10^{-25}\,\mathrm{MeV}^2\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{MeV}^{-1}$) from Fermi (points) with the calculations of the spectrum due to cosmic-ray interactions. The emissivity is dominated by $\pi^0$ production and decay (*blue curve*) but also has a contribution from electron bremsstrahlung (*red curve*). The total production is shown by the *black curve*. Panel **a** adapted from Kamae et al. (2006), **b** and **c** from Abdo et al. (2009)

electrons due to bremsstrahlung in interstellar collisions and by inverse Compton scattering on background photons.

Gamma-ray measurements have recently been reported (Abdo et al. 2009) from the Fermi/LAT instrument viewing regions of the sky that are out of the galactic plane and far from the galactic center and from known large molecular clouds. After applying corrections for point sources and inverse Compton scattering, the measured gamma-ray intensity from a number of lines of sight were plotted versus the column density of interstellar gas in those directions. As shown in Fig. 2b, strong correlations were found, indicating that cosmic-ray interactions in that gas are the dominant source of these gamma-rays. Comparison of derived gamma-ray emissivity with that calculated using the GALPROP program based on the estimated local interstellar proton spectrum yielded agreement within ∼10%, as shown in Fig. 2c, thus providing additional evidence for the correctness of the derived interstellar cosmic-ray spectra above several GeV.

Cosmic-ray collisions with interstellar gas and dust can also produce excited states of nuclei that subsequently decay emitting one or more gamma-rays with energies typically in the 0.1 to 10 MeV range. Since the threshold for these reactions is no more than a few MeV, the production should be dominated by the low-energy portion of the cosmic-ray spectrum that is not directly observable from inside the heliosphere. To date, searches for this galactic gamma-ray line emission have not yielded positive detections that could be substantiated (Teegarden and Watanabe 2006). However, calculations of expected yields (Ramaty 1996; Dogiel et al. 2009) indicate that future, more sensitive gamma-ray telescopes may be able to take advantage of this technique for constraining the low-energy portion of the interstellar cosmic-ray spectrum, at least in some regions of the Galaxy.

## 5.2 Ionization State of the Interstellar Gas

As discussed in Sect. 2, cosmic rays lose energy in the interstellar medium by ionizing collisions with interstellar gas atoms and molecules. Some specific chemical reaction chains that depend on an ionized reactant are enabled by the presence of this ionized material. When such reactions lead to the production of a molecule that would not otherwise be found in significant abundance in the interstellar medium, there is the possibility of using measurements of the concentration of this molecule to assess the rate of ionization, which in some environments should be predominantly due to cosmic rays. Such an environment should occur in diffuse interstellar clouds, since x-rays are absorbed in a thin layer at the cloud surface but cosmic rays can penetrate the entire cloud (Glassgold and Langer 1974), thus the densities of certain molecules should provide a measure of the cosmic-ray intensity. Recent reviews of this subject can be found in Dalgarno (2006) and Padovani et al. (2009). This ionization due to cosmic rays should be dominated by relatively low-energy particles both because they are probably the most abundant and because specific ionization decreases with increasing energy.

Some molecules that have been used as diagnostics of the ionization rate include OH, HD, and $H_3^+$, among others (Dalgarno 2006, and references therein). The sequence of reactions that determine density of the $H_3^+$ ion, the most abundant molecular ion in diffuse interstellar clouds, is particularly simple: first, $H_2$ is ionized to produce $H_2^+$ and a free electron; second, that $H_2^+$ reacts with another $H_2$ molecule to produce $H_3^+$ plus an H atom; and third, the $H_3^+$ reacts with a free electron and dissociates into $H_2$+H or 3 H atoms. The rate of the second step is fast compared to the first step (Indriolo et al. 2007) and the rate coefficient for the third step has been measured in the laboratory under conditions appropriate to diffuse interstellar clouds (McCall et al. 2003). So under conditions where the electron fraction, $n(e^-)/n(\mathrm{H}_2)$ can be estimated, the measured column density of $H_3^+$ allows a fairly direct determination of the primary cosmic-ray ionization rate, $\zeta_\mathrm{H}$, defined as the rate at which cosmic-ray protons directly ionize interstellar H atoms, not including ionization by secondary electrons. From measurements of the $H_3^+$ absorption line along a number of lines of sight, Indriolo et al. (2007) derived an ionization rate per H atom of $\zeta_\mathrm{H} \simeq 2 \times 10^{-16}\ \mathrm{s}^{-1}$ within a factor ∼2.

Webber (1998) attempted to calculate $\zeta_\mathrm{H}$ based on an estimate of the interstellar cosmic ray spectra derived from measurements by the Pioneer and Voyager spacecraft when the latter were near ∼60 AU. His result, $3\text{–}4\times 10^{-17}\ \mathrm{s}^{-1}$, which he characterized as "most likely a minimum value" is subject to large uncertainty due to the difficulty of extrapolating spectra from 60 AU to the local interstellar medium. Alternatively, one can examine the range of low-energy (less than a few hundred MeV/nucleon) cosmic-ray intensities that are compatible with the determination of $\zeta_\mathrm{H}$ from the $H_3^+$ studies. Considering interstellar energy spectra having the form of a power-law in proton kinetic energy down to some low-energy cutoff (Nath and Biermann 1994), one can derive the combinations of spectral index, intensity, and cutoff energy that yield the required value $\zeta_\mathrm{H} = 2 \times 10^{-16}\ \mathrm{s}^{-1}$. The results of such a calculation are shown in the left-hand panel of Fig. 3. The right-hand panel shows a number of power-law spectra added to one of the forms that have been suggested for the local interstellar proton spectrum (Usoskin et al. 2005, dashed curve) based on observations made at Earth (see also Herbst et al. 2010). The power law spectra are scaled to the maximum intensity that yield, to within $<1\%$ at all energies, the same 1 AU spectrum (red curve) as the Usoskin et al. (2005) spectrum alone when modulated using the same spherically symmetric model employed in the calculations for Fig. 1 with the solar minimum modulation parameter $\phi = 260$ MV. The power laws are shown with low-energy cutoffs that yield the required value of $\zeta_\mathrm{H}$.

Although there is no good basis for assuming that the low-energy portion of the cosmic-ray spectrum would have the form of a cut-off power law, these results do illustrate the fact that a very wide range of low-energy interstellar cosmic-ray spectra could be consistent

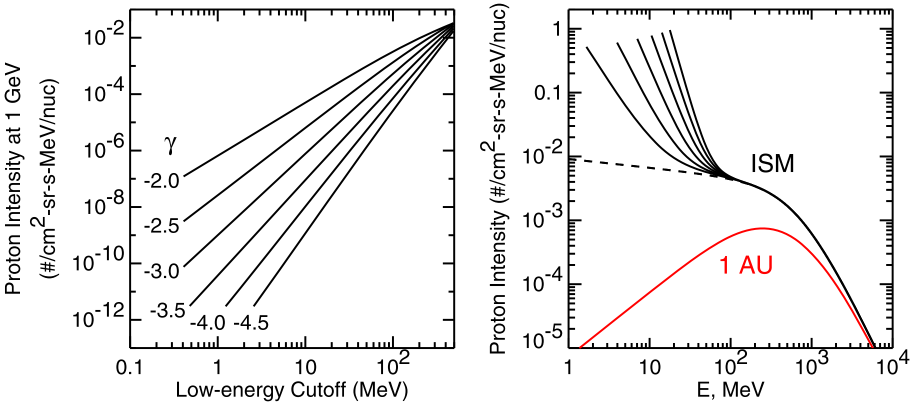

**Fig. 3** *Left panel*: Combinations of proton intensity at 1 GeV, low-energy cut-off energy, and spectral index ($\gamma$) for power-law energy spectra that yield the ionization rate $\zeta_H = 2 \times 10^{-16}$/s inferred from $H_3^+$ absorption studies (Indriolo et al. 2007). Right panel: interstellar proton spectrum (*dashed curve*) proposed by Usoskin et al. (2005) summed with various power-law spectra with intensities and low-energy cutoffs chosen such that they reproduce the inferred value of $\zeta_H$ and but still yield the same 1 AU spectrum to within 1% at all energies. For power-laws harder than the high-energy asymptote of the 1 AU proton spectrum, the power-law was cut off above 1 GeV

both with the spectral observations made at 1 AU and constraints derived based on cosmic-ray ionization effects on densities of interstellar molecules. Future detection of gamma-ray line emission excited by collisions involving cosmic rays with energies a few 10's of MeV (see Sect. 5.1) may be useful for investigating existence of low-energy spectral turn-ups. Indriolo et al. (2009) present a more detailed discussion of astrophysical constraints on the low-energy portion of the interstellar cosmic-ray energy spectrum.

## 6 Cosmic-Ray Time Variations in the ISM

At any particular location and time the cosmic-ray spectrum contains contributions of particles accelerated in a sizeable number of different supernova shocks. Propagation models of the sort discussed in Sect. 2 explicitly assume a steady state, and it is often assumed that sources have a uniform spatial distribution over some volume of the Galaxy. Therefore, such models do not address the question of how much the cosmic-ray spectrum in the local interstellar medium near the solar system can vary over time. A few studies (Pohl and Esposito 1998; Higdon and Lingenfelter 2000; Büsching et al. 2005) have modeled the effects of discrete acceleration events using Monte Carlo techniques.

The calculations of Büsching et al. (2005) showed that 10 GeV/nucleon oxygen nuclei accelerated in a supernova event should cause the intensity of this ion to increase by variable amounts ranging up to ~100% (depending on the distance of the supernova from the solar system) in a region of size ~100 pc and then decay back to the steady state background level in ~1 Myr The intensity of a primary cosmic-ray nuclide such as $^{12}$C in the interstellar medium near the solar system should be due to a superposition of such injections by supernovae occurring at various times and distances. For a secondary nuclide such as $^{11}$B, which is produced by fragmentation of $^{12}$C, the time variation is greatly reduced because the relatively low-probability nuclear fragmentation reactions that produce the secondaries cause smoothing over temporal scales of at least several Myr. Results from the Büsching et

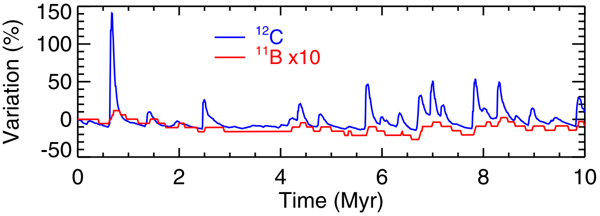

**Fig. 4** Simulated time variations of 10 GeV/nucleon GCR $^{12}$C and $^{11}$B intensities taken from the Monte Carlo calculations of Büsching et al. (2005). Note that the variations for the secondary nuclide $^{11}$B, which are much smaller than those for the primary $^{12}$C, have been multiplied by 10. The steps in the $^{11}$B curve are due to digitization of the Büsching et al. (2005) plot

al. (2005) calculation of the time variation of $^{12}$C and $^{11}$B are shown in Fig. 4. The situation for protons, which are accelerated episodically, and antiprotons, which are produced continuously as collision products, should be qualitatively similar.

The rate at which particles accelerated by a supernova shock are dispersed into the general interstellar medium depends on the interstellar diffusion coefficient and, therefore, on energy. However, Büsching et al. (2005) found that the shapes of the energy spectra of both primary and secondary species did not vary much among different Monte Carlo runs.

The situation for high-energy electrons is somewhat different. The rate of electron energy loss via synchrotron and bremsstrahlung emission becomes very fast at high energies (Kobayashi et al. 2004), so the relevant averaging time and distance scales for high-energy electrons and positrons is short and strongly energy dependent. The Monte Carlo model of Pohl and Esposito (1998), which assumes that cosmic-ray negatrons are accelerated primarily in supernova remnants, predicts one-sigma variations of $\sim$10%, $\sim$20%, and $\sim$100% at energies of 2, 10, and 100 GeV. For positrons produced as secondaries in hadron collisions, the source distribution is relatively smooth, similar to the situation for production of secondary nuclides. This should result in much smaller temporal variation of high-energy positrons than of high-energy negatrons.

Kawanaka et al. (2010) analyzed the case in which pulsars dominate the production of cosmic-ray negatrons and positrons. The discrete distribution of relatively short-lived sources leads to fluctuations for both charge signs that are expected to be similar to those found for electrons from supernova-remnant sources. There are quantitative differences due to the distributions and lifetimes of the different source types.

In considering cosmic-ray intensity ratios in which only one of the species being compared is expected to have a strong time dependence (e.g., $e^+/e^-$ at high energies, $\overline{p}/p$, or $^{11}B/^{12}C$) it is important to recognize that the value observed at the present time could deviate significantly from the long-term average calculated using steady-state models.

## 7 Summary and Conclusions

Considering the various cosmic-ray species that can be used as probes of solar modulation, there are very substantial differences in how reliably estimates of the local interstellar spectra can be made. At high energies, above several 10's of GeV (or GeV/nucleon for heavy elements), local interstellar spectra are rather well constrained by high-energy observations at 1 AU together with extrapolations to lower energy using simple propagation models. At energies below 1 GeV, most interstellar spectra are only weakly constrained. Important exceptions are the spectra of antiprotons, which are produced by interactions of high-energy protons, and electrons ($e^- + e^+$) below ∼1 GeV, for which the interstellar spectrum is constrained by observations of diffuse interstellar synchrotron and bremsstrahlung emission. However, both of these constraints involve observations that average over sizeable distances in the Galaxy, leaving some uncertainty since temporal and spatial variations may result in differences between values in the local neighborhood of the solar system and those derived from larger-scale averages. At low energies, below a few hundred MeV, very little is known about the local interstellar intensities of cosmic rays. Observations of molecular species that are sensitive to the ionization rate by cosmic rays, such as $H_3^+$ in diffuse interstellar clouds, provide a potentially useful constraint on low-energy cosmic-ray intensities, but the resulting limits are not particularly stringent.

The most reliable way to establish the present-day interstellar spectra of cosmic rays in the very-local interstellar medium is to send a space probe beyond the region of influence of solar modulation. If, as some people believe, this boundary coincides with the heliopause, then the Voyager spacecraft may greatly improve our understanding the low-energy interstellar spectra within the next decade. If solar modulation is occurring over a substantially larger volume, then an Interstellar Probe mission of the sort that has been the subject of several studies (Liewer et al. 2000; McNutt et al. 2000, 2010; Mewaldt and Liewer 2001) may be required.

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