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Voyager 1 Observations of Galactic Cosmic Rays from the Local Interstellar Medium

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Abstract: Since 25 August 2013 the Voyager 1 spacecraft has been in a region of the heliosphere where low-energy galactic cosmic rays (GCRs) apparently have easy access to the spacecraft. The local interstellar spectra of the GCR nuclei and electrons are likely being measured for the first time down to a few MeV/nuc or to a few MeV, respectively. Heretofore, this part of the spectrum for nuclei was composed of either particles of heliospheric origin or of GCRs of higher energy in interstellar space that have been decelerated during the solar modulation process. We present preliminary GCR energy spectra for eight elements from the Voyager 1 spacecraft for the period 2012/342-2013/161. We find that the C and O spectra have a broad peak in intensity in the 40-100 MeV/nuc range with a C/O ratio of 1.07 ± 0.04 from 21.6 - 106 MeV/nuc. The GCR H and He spectra are also rather flat below 100 MeV/nuc with a peak intensity near 10-40 MeV/nuc. The H/He ratio is 13.0 ± 0.2 from 7.8 - 57 MeV/nuc. We also report on the GCR electron spectrum from ∼6 - 70 MeV and find that a power-law with spectral index of -1.46 ± 0.09 is consistent with the observations.

Keywords: Voyager, galactic cosmic rays.

1 Introduction

As reported in [15, 7], on 25 August 2012 Voyager 1 (V1) entered a region of the heliosphere that was depleted of heliospheric ions and electrons. The direction of the magnetic field did not change appreciably [1], suggesting the spacecraft did not cross the heliopause into interstellar space. However, the intensity of galactic cosmic ray (GCR) ions and electrons jumped up in concert with the drop in the intensity of heliospheric ions and electrons, and the GCR intensities have remained reasonably steady since that time. This circumstance provides the first opportunity to examine the energy spectrum of GCR ions at lower energies than heretofore possible and to determine what may be the interstellar energy spectrum of electrons.

2 Observations and Discussion

The observations reported here are from the Cosmic Ray Subsystem (CRS) on V1 [16]. In Figure 1 we show the differential energy spectra of H, He, C and O from V1 for the period 2012/342-2013/161. The CRS telescopes used here are as described in [15] except that for O all four LET telescopes were used. The start of this period was chosen to coincide with the time when the O intensity with 5.4-13.9 MeV/nuc appears to have become isotropic after a period of ∼100 days of relatively large anisotropy following the 25 August 2012 onset of the heliospheric depletion region (see [15]). These spectra are updates to those shown in [15] for a later period when there was no significant contamination by heliospheric particles. The data shown in Figure 1 are thought to be GCRs uncontaminated by heliospheric particles. It is important to note that all prior measurements of GCRs in the heliosphere at the energies shown in Figure 1 were of particles that had higher energies in interstellar space before being decelerated by the solar modulation process. It is likely that the energy spectra in Figure 1

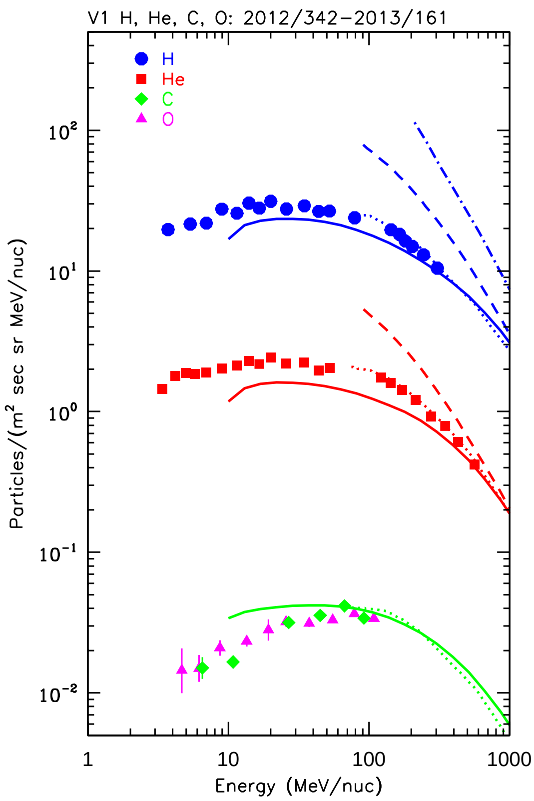

Figure 1: Differential energy spectra from V1. Estimates of the interstellar GCR spectra are shown and discussed in the text: GALPROP model (solid line); leaky box model [20] (dotted); DC model [10] (dashed); and pump acceleration model [4] (dot-dash).

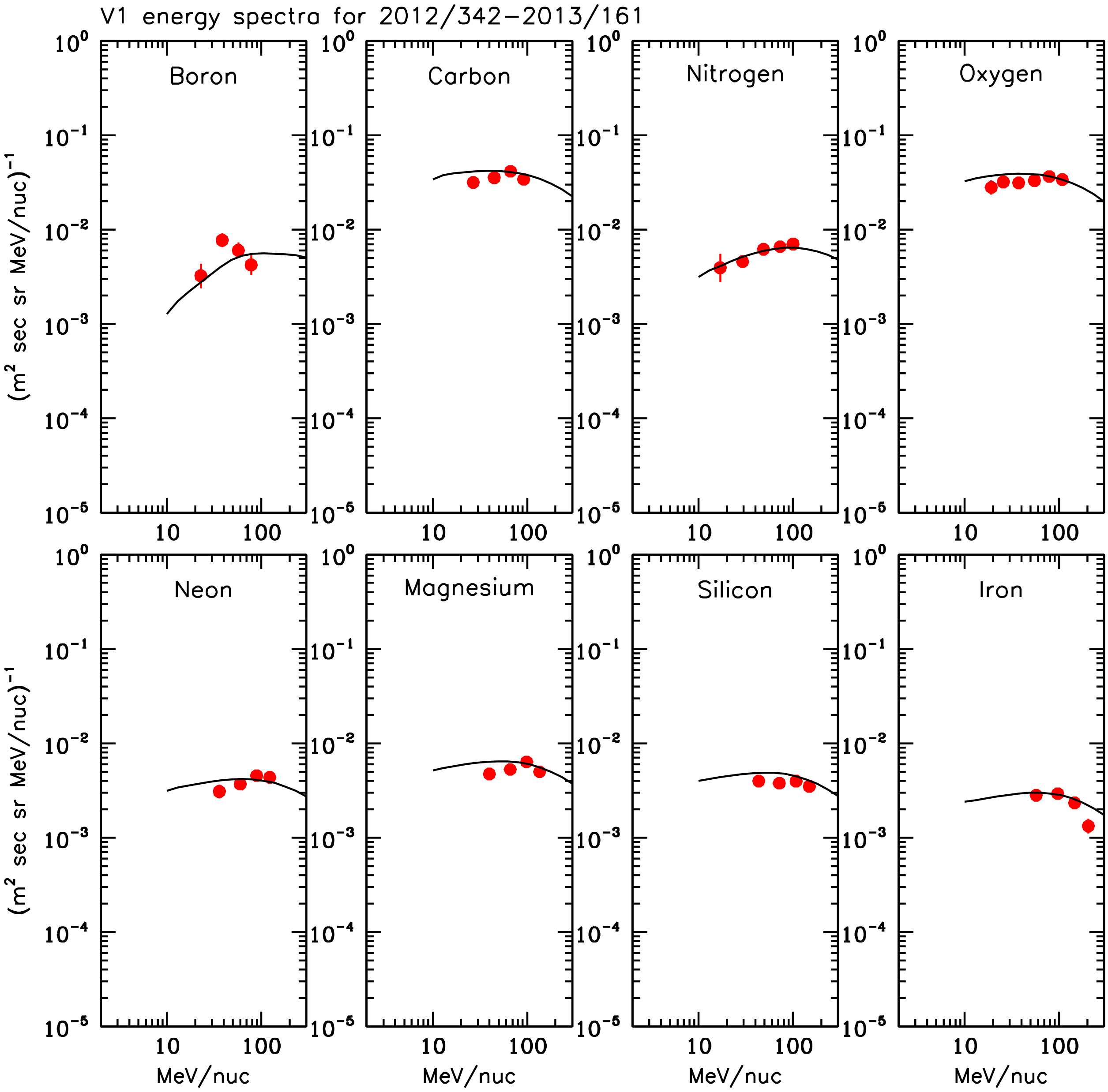

Figure 2: Preliminary differential energy spectra from V1 for the period 2012/342-2013/161. The line is a GALPROP conventional diffusive acceleration model that was tuned by [9] to fit ACE data at higher energies at 1 AU. The GALPROP results file is http://galprop.stanford.edu/wrxiv/results_54_0572000f_4fdgrmnry7ffy65y.tar.gz.

are the first to reveal the energy spectra present in the local interstellar medium (LISM). We have looked for possible spatial intensity gradients that would suggest there might be modulation of GCRs in the LISM [13, 5, 17] and have not found any [15].

Also shown in Figure 1 are several model estimates of the LISM energy spectra for H, He, and C. A conventional GALPROP (http://galprop.stanford.edu/webrun/) diffusive acceleration model that has been tuned to ACE data by [9] illustrates that ionization energy loss during propagation in the interstellar medium results in rather flat energy spectra for H and He, with broad maxima in the ∼10-40 MeV/nuc energy range. The GALPROP model intensities are typically 20-30% below the He and He observed intensities and about a factor of 3 higher than the C intensity at 15 MeV/nuc. The leaky box model from [20] matches the H and He data (and C data as well) down to ∼70 Mev/nuc, while the higher H and He model estimates of [4] and [10] would require significant solar modulation to fit the data.

We have determined ratios of H/He in three energy intervals: 11.7 ± 0.2 for 3-7.8 MeV/nuc; 13.0 ± 0.2 for 7.8-57 MeV/nuc; and 12.3 ± 0.1 for 134-346 MeV/nuc. The uncertainties quoted are statistical only; possible systematic uncertainties are under review. The previous measurement of the GCR H/He ratio at 1 AU where the GCRs have been decelerated from higher energies was 4.7 ± 0.5 at 100 MeV/nuc [14], well below that of the unmodulated spectra in Figure 1. Also, the Anomalous Cosmic Ray (ACR) H/He ratio is 4.1 [2], indicating that ACRs are not a major contributor to the low-energy GCR energy spectrum, contrary to a recent suggestion [12].

The C and O spectra have a broad intensity peak in the

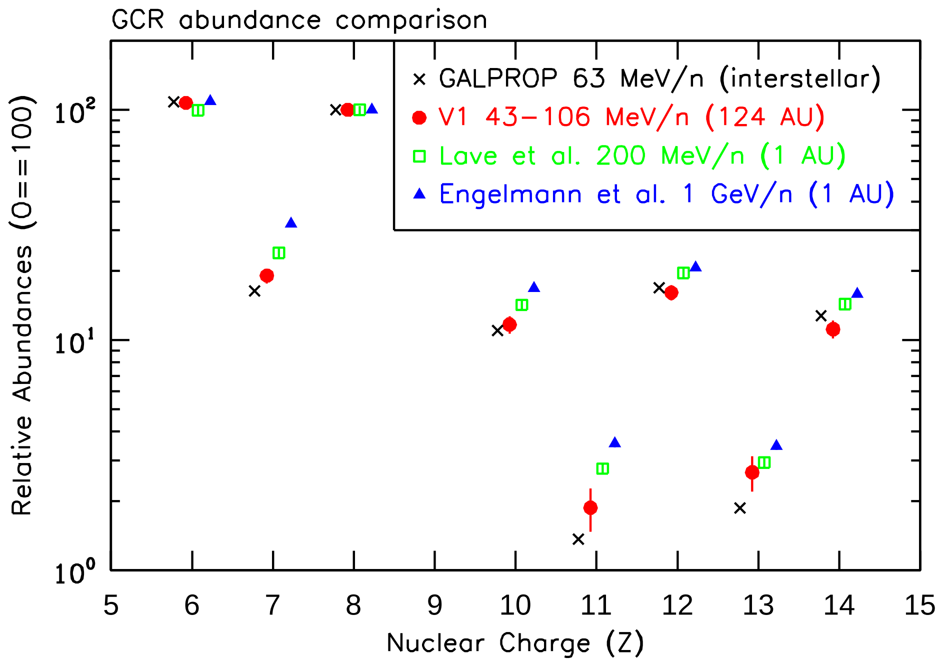

Figure 3: GCR abundances relative to O from the V1 observations in the energy range 43-106 MeV/nuc for the period 2012/342-2013/161 compared with those at higher energies [3, 9] at 1 AU where there is significant solar modulation. Also shown are the interstellar estimates from a GALPROP conventional diffusive reacceleration model that was tuned to ACE data at 1 AU by [9].

∼40-100 MeV/nuc energy range. The C/O ratio is 1.07 ± 0.04 in the energy range 21.6-106 MeV/nuc.

In Figure 2 we show preliminary differential energy spectra of six additional elements from V1 for the period 2012/342-2013/161: B, N, Ne, Mg, Si, and Fe, together with the C and O spectra. This figure shows data from only the High Energy Telescopes [16] where there are acceptable statistics in this preliminary data set. The observed spectra are reasonably well matched by the GALPROP model. Energy spectra down to a few MeV/nuc will be observable with more accumulation time.

The B/C ratio is of interest in GCR propagation studies because B is a purely secondary ion being produced in interactions of heavier GCRs with interstellar neutral atoms. We find the B/C ratio is 0.16 ± 0.02 in the energy range 31-90 MeV/nuc. Lave et al. [9] report a roughly energy-independent ratio of B/C of ∼0.22 from ∼70-170 MeV/nuc measured at 1 AU in 2009-2010. Unlike the strongly modulated B/C ratio at 1 AU, the interstellar ratio should decrease at lower energies because the B intensity is expected to significantly decrease with decreasing energy as illustrated by the GALPROP spectra in Figure 2.

In Figure 3 we show abundances of several other key ions from V1 during the period 2012/342-2013/161 for the energy interval 43-106 MeV/nuc. We also show abundances from observations at 1 AU by ACE and by HEAO-3 [9, 3]. Our observations differ significantly in some cases from those measured at 1 AU, partly because the nuclei at 1 AU are adiabatically cooled from higher interstellar energies where they are less affected by ionization energy loss during interstellar propagation than are lower energy nuclei (see, e.g., [6]). For most nuclei, the interstellar estimates from the GALPROP model that was tuned to the 1 AU ACE data [9] are in reasonable agreement with the V1 observations. The effects of ionization energy loss will become more apparent when observations extend to lower energies for more species.

We have also measured the GCR electron spectrum from V1 for the period 2012/342-2013/161 using the techniques described in [15]. The energy spectrum is shown in Figure 4 along with several estimates of the interstellar electron spectrum. Two power-laws are shown, based on two sets of response functions derived in different ways [15]. Using the Geant4 simulation, the resulting power-law fit to the data is $dJ/dE = 284(E/10)^{-1.37}$, where E is energy in MeV. Using the response functions from the pre-flight accelerator calibration, the power-law fit is $dJ/dE = 276(E/10)^{-1.55}$. A rough estimate of the spectral index is thus -1.46 ± 0.09.

The observed energy spectrum is approximately a factor of 2 or more above the estimated interstellar spectrum of [19, 11] and a factor of 2 below model estimates of [8, 6]. Two energy spectra are also shown from [18], one using an electron source spectrum with an injection spectral index of -1.6, their favored model, and one using an injection spectral index of -2.0, which would join onto the observations better. Matching these interstellar estimates to the observations should improve our understanding of conditions in interstellar space.

3 Summary

This report updates recently reported observations of GCR ions by V1 that for the first time reveal spectra that have broad intensity peaks at energies below ∼100 MeV/nuc and that have not been modified by adiabatic deceleration effects in the heliosphere nor contaminated by heliospheric particles. New observations of the GCR electrons reveal

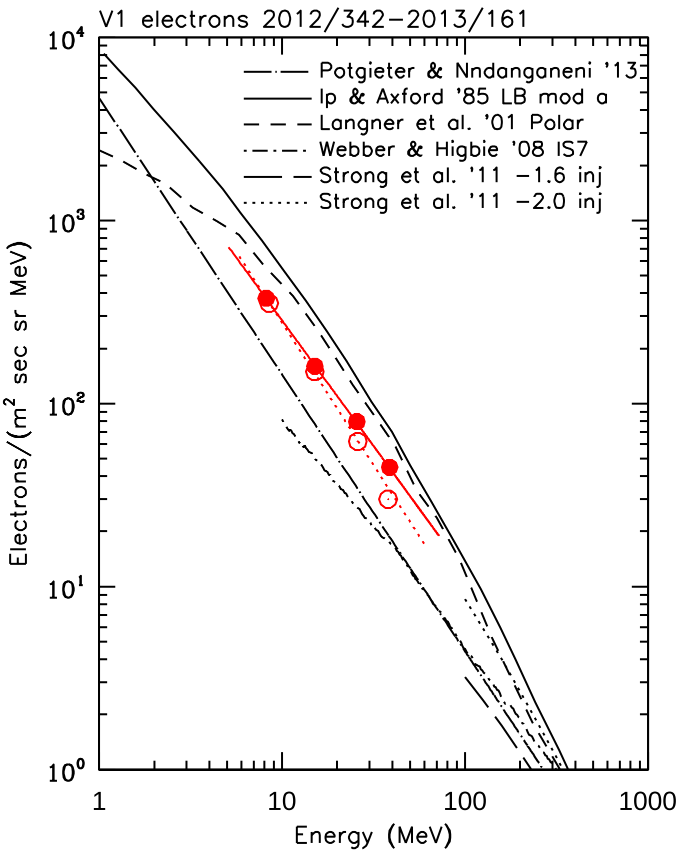

Figure 4: Differential energy spectrum of electrons from V1 for the period 2012/342-2013/161. The open symbols represent analysis done using response functions derived from a pre-flight calibration at an electron accelerator. The solid symbols represent the energy spectrum derived from a simulation using the Geant4 software (www.geant4.cern.ch). The differences between the results of the two methods gives an indication of the systematic uncertainty.

an energy spectrum that increases with decreasing energy down to less than 10 MeV.

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