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Re-Accelerated Solar Wind – An Additional Source of Anomalous Cosmic Rays?

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Abstract

We consider the acceleration of solar, interplanetary, and interstellar particles at the solar-wind termination shock, predict expected composition and energy spectra, and discuss possible observable consequences. The acceleration of a small fraction of solar wind ions incident on the termination shock may explain low-energy enhancements in the spectra of several elements observed by Voyager beyond ~ 60 AU. Other possible particle sources are also discussed.

1 Introduction:

Anomalous cosmic rays (ACRs), including H, He, C, N, O, Ne, and Ar, originate from interstellar neutral particles that have been swept into the heliosphere and ionized to form pickup ions, which are then convected into the outer heliosphere and accelerated to ~5 to 50 MeV/nuc. The bulk of ACR acceleration occurs at the solar wind termination shock (e.g., Jokipii 1990). The termination shock is also expected to accelerate (or re-accelerate) other particles species. Mewaldt (1995, 1999) considered the re-acceleration of low-energy ions that originate in solar and interplanetary sources and pointed out possible observable consequences. Suggested seed populations include solar energetic particles (RSEPs), re-accelerated solar wind (RSW), and ions energized by co-rotating interaction regions. These re-accelerated components provide a possible explanation for enhancements in the low-energy spectra of Mg, Si, S and other elements observed by Voyager 1 & 2 during beyond 60 AU (Stone and Cummings 1997; Cummings and Stone 1999). There are also unexpected and unexplained increases in the low-energy spectra of several elements reported at 1 AU (e.g., Takashima et al. 1997; Klecker et al. 1998; Reames 1999).

In this paper we extend the discussion of RSW particles in Mewaldt (1999) to other species, and to 1 AU, consider new estimates of the neutral populations of elements in the ISM that might contribute additional ACR species, and also discuss other possible particle sources.

2 Seed Populations at the Termination Shock:

2.1 Anomalous Cosmic Rays: Elements with first ionization potential (FIP) values ≥ 13.6 eV (e.g., H, He, N. O, Ne, and Ar), generally have a significant neutral abundance in the local interstellar medium (ISM), while those with FIP < 13.6 eV are almost entirely ionized. In addition, large fractions (e.g., 50% to 90% or more) of refractory elements such as Mg, Si, and Fe are condensed into interstellar grains (e.g., Frisch 1998). As a result, the neutral abundances of these refractory species are very much less than those of N, O, and Ne.

Frisch and Slavin (1999) have estimated the abundances of common elements in our local interstellar cloud (LIC) that reside in the form of interplanetary dust, neutral particles, and singly-charged ions. Cummings and Stone (1996) estimated the intensity of several pickup ion species incident on the termination shock. These estimates have been extended to other species following Mewaldt (1999). Cummings et al. (1990), find that the fraction of neutral interstellar C that get ionized in the heliosphere is ~27%. The fraction of heavier, more easily ionized species such as Mg, Si, S, and Fe that get ionized will be greater; as an estimate we assume 50% are ionized as they pass through the heliosphere. Table 1 includes the resulting pickup ion fluxes at the termination shock (assumed to be at 80 AU).

2.2 Re-Accelerated Solar Wind: Monte Carlo simulations demonstrate that the termination shock can also accelerate a small fraction of solar wind (Ellison et al. 1998), and Mewaldt (1999) found that the re-acceleration of ~0.2% of the solar wind ions incident on the shock might account for the observed fluxes of Si, S, and Fe reported by Stone and Cummings (1997). To estimate the flux of other solar wind species we use the summary by von Steiger and Geiss (1997), supplemented by solar system abundances from Anders and Grevesse (1989).

2.3 Vaporized Interplanetary Dust: Geiss et al. (1995) have reported an additional source of pick-up ions in the inner heliosphere, including C, O, and possibly heavier species, that are attributed to dust grains vaporized near the Sun. They estimated that this source might account for ~20% of pickup C incident on the termination shock. While this "inner" source might also contribute to other refractory elements, it would not be expected to contribute any S.

Table 1: Seed Particle and Accelerated Abundances

	Assumed RSW mean	Peak Energy (MeV/nuc)		80 AU Flux (per cm2sec)		Estimated Flux at 8 MeV/nuc & 60 AU (per cm2 sr sec) x 10^5	
Element	Charge State	ACRs	RSW Ions	Pickup Ions	Solar Wind	ACRs	RSW Ions
He	2	6.0	12.0	216	2142	1 x 10^6	2930
C	5.4	2.0	10.8	0.0052	20.6	53	41
N	5.5	1.7	9.4	0.9	3.7	6800	11
O	6	1.5	9.1	8.5	28.6	6.5 x 10^4	89
Ne	8	1.2	9.5	0.29	4	2430	11
Na	8.9	1,0	9.3	1.8E-04	0.28	0.7	1
Mg	9.5	1.0	9.4	7.3E-04	4.6	5.3	13
Al	9	0.9	8.0	1.0E-06	0.33	0.06	1.6
Si	8.6	0.86	7.3	4.4E-05	5.3	0.3	23
S	8.8	0.75	6.5	6.5E-05	1.3	0.3	5
Ar	9.1	0.66	6.0	2.4E-02	0.11	55	0.6
Ca	10	0.60	6.1	-	0.57	-	1.6
Fe	10	0.43	4.3	2.3E-05	4.9	0.02	26

3. Composition and Energy Spectra of Accelerated Particles

The energy spectra of ACRs have a generic shape that scales with the mass to charge ratio (A/Q) of the ions (Cummings et al. 1984), where Q=1 for most ACRs. To represent the ACR spectra at 60 AU we adopt an exponential form with a maximum intensity at $Ep = 24\ (A/Q)^{-1}$ MeV/nuc, and use, as an example, mean charge states characteristic of 1.3 MK (Arnaud and Rothenflug 1985). Table 1 shows the predicted location of the peak flux for ACRs (with Q=1) and for RSW ions at 60 AU during 1993-1996. Note that most heavy RSW ions have A/Q ratios similar to ACR He. The following spectral is used for both ACRs and RSEPs (Mewaldt 1999):

$$dJ/dE = KF(A/Q)^{1.5}\exp[-A(E - Ep)/72Q] \qquad (E \geq Ep) \qquad (1)$$

and

$$dJ/dE = KF(A/Q)^{1.5}\exp[-A(E-Ep)^2/72Q] \qquad (E<Ep) \qquad (2)$$

In the above F is the pickup-ion or solar-wind flux at the shock (Table 1). The only free parameter is K, the efficiency for injection into the accelerator. By fitting Voyager data Mewaldt (1999) found K for solar wind ions to be ~0.002 of that for pickup ions.

The estimated contributions from GCR, ACR, and RSW ions to 13 elements are shown in Figure 1, along with available Voyager-1 fluxes at ~8 MeV/nuc. Within the uncertainties, the RSW contributions provide a possible explanation for the ~5 to ~20 MeV/nuc Voyager observations of Si and S. The ACR contributions, which peak at much lower energies, match the measured fluxes of He, N, O, Ne, and Ar reasonably well, but fall far short for Si and S, and do not account for all of the observed C. It does not appear as if the neutral abundances that Frisch and Slavin (1999) predict for rare ACR species such as Na, Mg, Al, Si, S, Ca, and Fe would be observable above the GCR background at energies >5 MeV/nuc. However, if the RSW source accounts for the Mg, Si and S enhancements, it might also be observable for several other species at somewhat lower intensity levels.

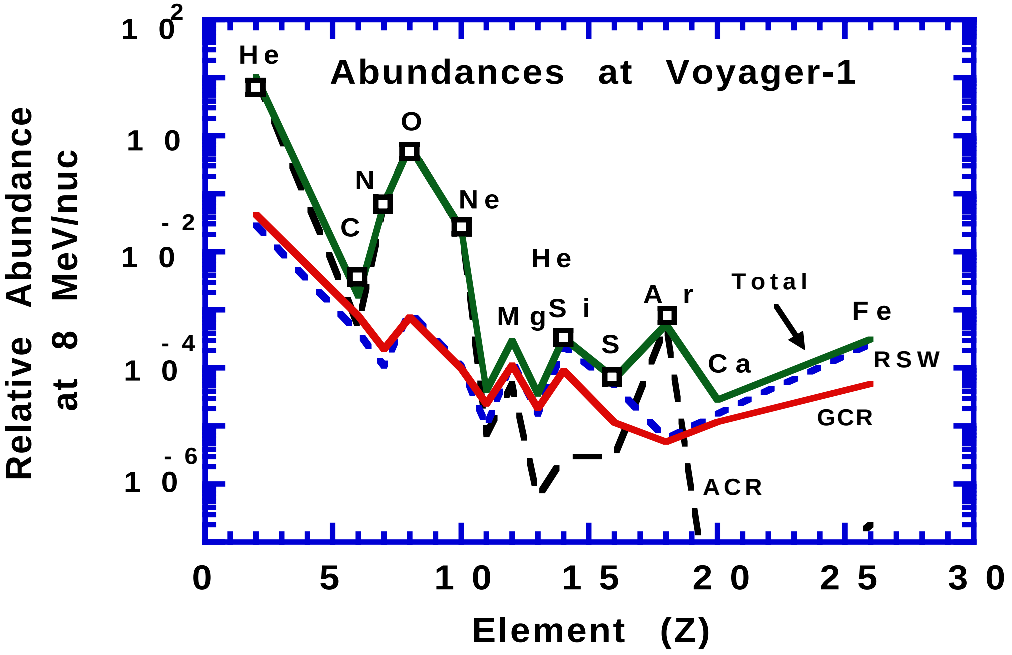

Figure 1: The estimated contributions of anomalous cosmic rays (ACR), galactic cosmic rays, (GCR), and re-accelerated solar wind (RSW) are compared to Voyager-1 observations at ~60 AU (Stone and Cummings, 1997). All contributions are evaluated at a common energy of 8 MeV/nuc.

3.1 Spectra at 1 AU: There have also been reports of low-energy enhancements for a number of rare species at 1 AU, including C, Mg, Si, and S (Takahashi et al. 1997; Klecker et al. 1998; Reames 1999). Reames (1999) finds that Mg, Si, and S peak below 5 MeV/nuc, while C peaks at higher energies. For the RSW source the predicted peaks for these species are all at ~10 to 15 MeV/nuc, similar to those for ACR He which has a similar Q/A ratio. As a result, the RSW source might contribute to C, but it does not appear consistent with the observed spectra of low-energy Mg, Si, and S unless our scaling of the expected spectral shape is in error. On the other hand, the ACR contributions to Mg, Si, and S are also much lower than required (when normalized to Ne and Ar, for example). A possible reconciliation of the RSW peak locations at 1 AU might result if the high-latitude solar wind is the main contributor, in which case the ions would not be accelerated to such high energies because they drift through less potential difference (Jokipii 1990). It is also possible that the low-energy Mg, Si and S at 1 AU are a residual solar/interplanetary component, possibly accelerated by CIRs or other interplanetary shocks.

4. Discussion

The calculations summarized in Table 1 and Figure 2 provide good fits to the common ACR species using theoretical pickup ion abundances appropriate to the local ISM. However, for Mg, Si, S, the estimated ACR fluxes (based on estimated neutral abundances in the ISM) are 10 to 100 times too small to account for the Voyager fluxes (see Figure 2). It appears, therefore, that an additional source is required. It is inevitable that the termination shock will re-accelerate some solar-wind ions; only the injection efficiency is unknown. We can also expect some acceleration of the “inner source” of pickup ions, but in this case the expected abundances would not include S. Following Ocam’s Razor, it is unlikely that there are multiple sources of ions (in addition to ACR species) barely peaking out above the background. The new source most likely to contribute appears to be the solar wind, which may explain the low energy enhancements of S, Si, and Mg, and may also contribute to C. Since the expected RSW contribution is only a few percent of the abundant ACR elements (He, N, O, Ne and Ar), there is no conflict with the accepted origin of these species from pickup ions. If the Voyager observations Mg, Si, and S do originate from re-accelerated solar, other elements such as Na, Al, and Ca will also be present (see also Table 1). .

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