processes in the heliosphere. The presently available data on the ionic charge composition provide the basis for future more detailed comparisons of the ACR charge composition with model calculations.

9. A Search for Minor Ions in Anomalous Cosmic Rays

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9.1. Introduction

There are presently seven elements that are generally recognized as members of the ACR component: H, He, C, N, O, Ne, and Ar. All of these, except C, have relatively high first ionization potentials, ranging from $\sim$ 13.6 eV for H to $\sim$ 24 eV for He. It is therefore expected that a large fraction of these species are in a neutral state in the local interstellar medium (LISM). Carbon, with its lower first ionization potential ($\sim$ 11 eV), is expected to be mostly ionized in the LISM. Recently, Reames *et al.* (1996) and Takashima *et al.* (1997) reported possible evidence for ACR sulfur at 1 AU. Sulfur has a first ionization potential of $\sim$ 10.4 eV, similar to C, and somewhat higher compared to neighboring elements such as Mg ($\sim$ 7.6 eV) and Si ($\sim$ 8.1 eV). In an effort to verify these new S results, Stone and Cummings (1997) examined Voyager 1 and 2 data from the outer heliosphere. They found enhanced abundances of Si, S, and Fe, which they attributed to anomalous cosmic rays. However, the relative abundance of S they observed was much less than that reported at 1 AU (see also Table VIII) suggesting that there may be an additional source of low-energy S or that none of the S is of ACR origin.

The present situation with S may be similar to that with ACR C. Beginning with the discovery of ACR ions more than 20 years ago, the quiet time analysis of low energy interplanetary spectra of C and O in the inner heliosphere generally showed C/O ratios of $\sim$ 5–15% (Oetliker *et al.,* 1997b, and references therein), much higher than expected from an interstellar source. The first convincing evidence for ACR C was presented by Cummings and Stone (1988) based on Voyager data from $\sim$ 20 AU during the 1987 solar minimum. The observed C/O ratio was $\sim$ 0.01, consistent with the interpretation that only a small fraction of C is neutral in the LISM. Using Ulysses data, Geiss *et al.* (1995) reported evidence for an additional "inner source" of C, N, and O: they observed an enhanced abundance of C among pickup ions at distances $\lesssim$ 4 AU, which they attributed to contributions from interstellar dust. However, a quantitative estimate showed (Geiss *et al.,* 1996) that the total production of C^+ and O^+ from this inner source is only of the order of $\sim$ 0.1% as compared to the total production of O^+ from the interstellar gas and does not contribute significantly to O (or N) in the ACRs. However, its contribution to ACR C may not be negligible and could be of the order of $\sim$ 10%. In a recent SAMPEX analysis, Mewaldt *et al.* (1996a) and Oetliker *et al.* (1997b) used the Earth's magnetic field as a rigidity spectrometer to filter out high charge states from the low-energy quiet-time spectra and obtain a "pure" sample of ACRs. They found ACR C/O ratios of 0.014± 0.009 (17–42 MeV/nuc) and 0.021 ± 0.009 (8–20 MeV/nuc), respectively, consistent with the observations by Voyager in the outer solar system. These low abundances indicate that most low-energy C at 1 AU in interplanetary space is not singly charged, as expected for ACRs, and that additional sources may contribute to the quiet-time fluxes at 1 AU.

In this section we report preliminary results of an extension of the SAMPEX geomagnetic filter approach, including data from mid-1992 to early 1996, as measured with the HILT (Klecker *et al.,* 1993) and MAST (Cook *et al.,* 1993) instruments on SAMPEX. The advantage of this approach is that particles of galactic origin, which are essentially fully stripped, or of solar and interplanetary origin (e.g. SEP, CME), which have high charge states characteristic of coronal temperatures of about $2 \cdot 10^6$ K (Luhn *et al.,* 1984, Oetliker *et al.,* 1997a, and references therein), are filtered out, leaving a pure sample of ions with low charge states (e.g., $q = +1, +2$, etc).

9.2. Observations

SAMPEX is in a near polar orbit (82° inclination) that cuts across geomagnetic cutoffs from ~ 0 to ~ 15 GV four times per orbit. Using particle trajectory calculations and empirical geomagnetic cutoff relations derived from fully-stripped galactic cosmic rays and solar energetic particles (see Klecker *et al.,* 1995; Mewaldt *et al.,* 1996a), it is possible to filter out GCR and SEP nuclei as well as trapped ACRs (Selesnick *et al.,* 1995) to obtain a "pure" sample of ACRs. HILT covers the low energy range from ~ 8 to 28 MeV/nuc (for O), while MAST covers the higher energy range, varying from 14–32 MeV/nuc for C to 29–60 MeV/nuc for Fe, in this analysis. Relative abundances of C, O, Ne, Mg, Si, S, Ar, and Fe with low charge states have been obtained over a large energy range (Table VII).

At low energies, using HILT data during the time period September 1992 to July 1995, and following the approach of Oetliker *et al.* (1997b), relative abundances of ions with low charge states in the energy range ~ 8–20 (C–Ne) and ~ 10–20 MeV/nuc (Mg–Fe) have been derived from ionic charge analysis. At higher energies, the geomagnetic filter approach has been used to discriminate against high charge states by selecting data from mid latitudes of ~ 52° to 65°, where highly charged ions do not have access (Mewaldt *et al.,* 1996a). Figure 26 shows that in the MAST energy range for Z>10 only 1 Mg and 1 Si count have been observed. The results on elemental composition are summarized in Table VII. The abundances reported recently from interplanetary measurements at 1 AU (Reames *et al.,* 1996; Takashima *et al.,* 1997) and in the outer heliosphere (Stone and Cummings, 1997) are summarized in Table VIII.

The abundances of Si and Ar with $q < 4$ are compatible with the observations in the outer heliosphere. However, somewhat surprisingly, the upper limit for singly charged Ar is significantly smaller than both the interplanetary measurements in

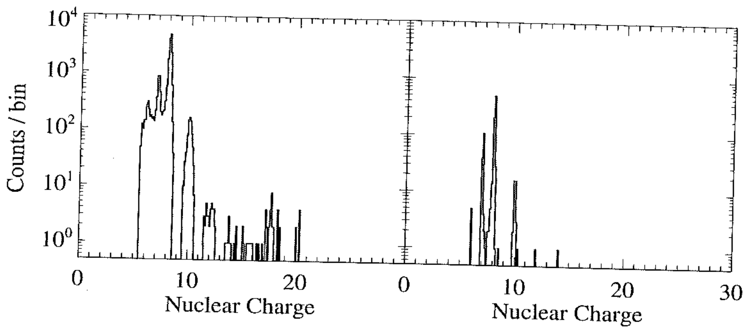

Figure 26. Histogram of events with low charge states from HILT (left) and MAST (right).

Table VII

Summary of elemental abundances derived with the geomagnetic filter approach at intermediate latitudes and from trapped particles at low latitudes (1 σ errors are given in parentheses)

Element	Z	Energy (MeV/nuc)	HILT ($q = 1$)	HILT ($q < 4$)	Energy (MeV/nuc)	MAST Filtered	MAST Trapped
C	6	7–20	0.9 (0.5)	2.7 (1.1)	14–32	0.7 (0.4)	0.08 (0.03)
O	8	8–20	70	86	17–42	100	100
Ne	10	9–20	3.5 (0.3)	4.5 (0.6)	19–46	6.3 (1.1)	3.0 (0.25)
Mg	12	9–20	0.07 (0.03)	0.1 (0.03)	21–51	<0.7	<0.05
Si	14	10–20	<0.03	<0.07	22–56	<0.7	<0.06
S	16	10–20	<0.03	<0.10	24–60	<0.5	<0.09
Ar	18	10–20	<0.02	0.10 (0.03)	25–60	<0.6	<0.11
Fe	26	10–20	<0.02	<0.02	29–60	<0.7	<0.23

the outer heliosphere and at 1 AU. The upper limit for Fe with $q < 4$ is also significantly smaller than the abundance observed at Voyager. The upper limit of S^+/O is compatible with the abundance in the outer heliosphere. However, the interplanetary S/O ratio in the outer heliosphere is significantly smaller than at 1 AU, as reported by Stone and Cummings (1997).

We have also searched for evidence of ACRs with $Z > 10$ in the radiation belt at low latitudes (L$\sim$ 2) composed of trapped ACRs (see, e.g., Selesnick *et al.*, 1995). Among more than 13,000 trapped C, N, O, and Ne nuclei observed by MAST there were no nuclei heavier than Ne (see Table VII). This places limits on the interplanetary abundance of singly or doubly charged ACRs with $Z > 10$, but they are difficult to quantify because of uncertainties in the trapping process. Note, however, that if heavy ACR nuclei have charge to mass ratios of $A/q \lesssim 12$, they are not likely to be trapped (see discussion below and Selesnick *et al.*, 1995).

Table VIII

Summary of elemental abundances from quiet time measurements in interplanetary space. The data are taken from Reames *et al.* (1996)[1], Takashima *et al.* (1997)[2], and Stone and Cummings (1997)[3]

Element	Z	Geotail[2] ~10 (MeV/nuc)	Wind[1] ~10 (MeV/nuc)	Geotail[2] ~20 (MeV/nuc)	Voyager[3] ~6–20 (MeV/nuc)
C	6	9	2.9	18	~2.0
O	8	100	100	100	100
Ne	10	5	6	4.4	4.8
Mg	12		0.23		
Si	14	0.25		1.0	~0.07
S	16	0.10		0.24	~0.02
Ar	18		0.25		~0.15
Fe	26			0.83	~0.07

9.3. Discussion

The geomagnetic filter approach to discriminate against high charge states provides a valuable tool to derive the composition of a "pure" ACR sample in the inner heliosphere. It has been demonstrated that most of the low energy quiet time C observed in interplanetary space at ~ 1 AU is not of ACR origin. However, the observed C/O ratio of ~ 1% for low charge states is compatible with the observations in the outer heliosphere where contamination by solar / interplanetary particles is apparently less significant. Table VII shows that abundances derived for low charge states ($q < 4$) at ~ 10 MeV/nuc are in general consistent with the abundances observed in the outer heliosphere, with the exception of Fe, where low charge states are significantly less abundant. This also seems to be true for singly ionized Si and Ar with energies > 10 MeV/nuc.

The interplanetary measurements at ~1 AU and in the outer heliosphere are not consistent for C and S. Although there is no direct evidence from the S ionic charge measurement, this suggests that at ~1 AU a significant fraction of S (as most of C) may be from a highly charged solar or interplanetary component. The low energy (< 10 MeV/nuc) S/C ratio of ~ 0.015 as observed at 1 AU (Takashima *et al.*, 1997) is, for instance, only a factor of ~ 2 smaller than coronal hole type solar wind composition (~ 0.031, Shafer *et al.*, 1993) and a factor of ~ 4 – 5 smaller than typical in-ecliptic solar wind (~ 0.053-0.07, Geiss *et al.*, 1994) or SEP composition (~ 0.08, Breneman and Stone, 1985).

If low energy Si and Fe as measured by Voyager are of ACR origin, then the low abundances of Si^+ and Fe^+ at 1 AU (as of Ar^+) could qualitatively be understood in terms of the acceleration process: the maximum energy particles of charge q can gain at the termination shock is ~ 240 q (MeV) (Jokipii and Giacalone, 1998).

This is consistent with the observation that the energy per nucleon above which multiply charged ions dominate is decreasing with mass (Selesnick *et al.*, 1997; Section 8). Using the value of 350 MeV for the energy where the abundances of singly charged ions drop to 50%, as derived in Section 8 for ACR N, O, and Ne, the corresponding energy per nucleon for Si, Ar, and Fe would be 12.5, 9.7, and 6.3 MeV/nuc. Therefore, in the energy range ≥ 10 MeV/nuc not many singly ionized Ar and Fe ions would be expected. Furthermore, the abundance of multiply charged ions will also depend on the charge exchange cross sections. For example, the cross sections for stripping 1 or 2 electrons from Ar^+ at 2 MeV, i.e. near the energy range of the maximum stripping cross section, are a factor of ~ 2.5 larger than the corresponding cross sections of oxygen (Lo *et al.*, 1971). For Fe the corresponding cross sections are a factor of ~ 2 smaller than for oxygen, and do not provide an explanation for increased losses. Thus, the question of the source of low energy S, Si, and Fe needs further investigation. Interplanetary measurements with improved collecting power or closer to the termination shock, in combination with ionic charge analysis and model calculations for minor ions will help to improve our understanding of rare ACR species.

10. Summary

As we conclude this chapter it is appropriate to revisit the "Top Ten Questions in Anomalous Cosmic Ray Studies" listed in Table I, in order to assess in which areas there has been progress.

Questions 1 and 2 concern possible additional species and/or sources of ACRs. The search for rare ACR ions in Section 9 demonstrates the power of the geomagnetic technique for addressing this question; this approach can separate partially-ionized from fully-stripped ions. This work provides confirming evidence that there are at least two sources of low energy carbon ions at 1 AU in addition to the low-energy tail of the modulated GCR component. There is apparently an interstellar neutral source with C/O $\sim$ 0.01–0.02 that is consistent with Voyager observations, and also an additional source of ions of unknown origin that appear to be dominated by intermediate charge states ($2 \leq q \leq 5$).

Section 9 also indicates that the low-energy sulfur component reported by Wind and Geotail (Reames *et al.*, 1996; Takashima *et al.*, 1997) may partly have an origin other than the neutral ISM, since apparently little of these S ions are singly-charged. In addition, there appears to be low-energy Mg, Si, and Ar ions that are neither fully-stripped nor singly-charged. The Ar is likely of interstellar neutral origin that (at energies >8 MeV/nuc) has been stripped to charge states of $q > 1$ during the ACR acceleration process (see below). The origin of the partially-ionized Mg and Si ions remains unclear, but it is evident that this field will continue to be one of vigorous investigation over the coming years.

Questions 3, 4, and 5 are concerned with the injection of pickup ions into the acceleration process, with the observed mass dependent acceleration efficiency and with the possible pre-acceleration of pickup ions in the heliosphere. It has been shown that acceleration in the inner heliosphere by CIRs and in the outer heliosphere by stochastic acceleration, in particular in corotating merged interaction regions, could significantly contribute to the particle population finally accelerated to ACR energies at the termination shock. It has also been demonstrated that the increase of the acceleration efficiency with mass could be reproduced in the mass range 1 to 4, at least qualitatively. However, a corresponding increase at higher masses could not be shown yet. As the next step, the pre-acceleration models including representative elements (e.g. H^+, He^+, O^+) have to be combined with models for acceleration at the termination shock and propagation in the heliosphere to fully understand the processes governing ACR injection, acceleration and propagation in the heliosphere (see below).

It was not expected that new measurements of ACR gradients and energy spectra would lead immediately to improved interplanetary diffusion coefficients and other transport parameters (Question 6), but the spacecraft data sets that are compiled in Section 2 represent a necessary first step towards this goal by providing bench mark data sets against which new models of cosmic ray transport in the heliosphere will be measured. The modeling efforts in Section 3 manage to fit the spectra of H and He individually, but do not yet provide a self-consistent fit to both ACR H and He. However, this model is being actively pursued and improved results have already been reported (C. D. Steenberg, private communication). In addition, new data continue to be added to the ACR archive at ISSI.

Although we are only beginning to realize the implications of multiply-charged ACRs (Questions 7 and 8), the report in Section 8 provides clear evidence that multiply-charged ACRs are common to other ACR species besides oxygen, and it suggests a pattern to the energy range where they predominate. Based on SAMPEX data for N, O, and Ne, it appears that singly-charged ACRs dominate below a total kinetic energy of $\sim$ 350 MeV, while multiply-charged ACRs dominate at higher energies. This pattern appears to be consistent with Jokipii's model of diffusive shock-drift acceleration, in which the spectra of accelerated species are expected to steepen significantly above a characteristic energy of $\sim 240q$ MeV (e.g., Jokipii, 1996).

In their review, Cummings and Stone (1998) provide evidence that the spectrum of accelerated ions observed as Voyager approaches the termination shock has a spectral index of –1.3, suggesting that the solar wind termination shock may be a weak shock, with a strength s of <2.8. Although none of the studies presented in this chapter address this observation specifically, during the discussions at the workshop a second possible interpretation was suggested. In the diffusive shock-drift acceleration model, the accelerated ions gain energy largely by drifting towards the poles of the heliosphere (during the current $qA > 0$ phase of the solar cycle), suggesting that the highest energy particles end up in the polar regions. Thus, if the potential energy gained by drift is indeed significant, one might expect the accelerated spectra in the polar regions to be harder than predicted for a given shock strength, while at lower latitudes the spectra near the shock would be softer than expected from simple shock-acceleration theory (the Voyagers are both located below 35° latitude). It should be possible to test this suggestion with multi-dimensional acceleration and transport models.

According to the latest predictions, Voyager 1 may cross the termination shock sometime before 2003 (e.g., Cummings and Stone, 1998). With the wealth of data now available from present solar minimum, it appears quite reasonable to expect that extensions of present models will have predictions available from a reasonably complete and self-consistent ACR acceleration/transport model (Question 10) in time for direct in situ testing by Voyager 1. It will be an additional challenge to ensure that such models are also consistent with the well-documented behavior of galactic cosmic rays (see also the Chapter of Working Group 1).

References

Achterberg, A., Blandford, R.D. and Reynolds, S.P.: 1994, 'Evidence for enhanced MHD turbulence outside sharp rimmed supernova remnants', *Astron. Astrophys.* **281**, 220–230.

Adams, J.H., Jr., Garcia-Munoz, M., Grigorov, N.L., Klecker, B., Kondratyeva, M.A., Mason, G.M., McGuire, R.E., Mewaldt, R.A., Panasyuk, M.I., Tretyakova, Ch.A., Tylka, A.J. and Zhuravlev, D.A.: 1991, 'The charge state of the anomalous component of cosmic rays', *Astrophys. J. Lett.* **375**, L45–L48.

Baker, D.N., Mason, G.M., Figueroa, O., Colon, G., Watzin, J.G. and Aleman, R.M.: 1993, 'An overview of the solar, anomalous and magnetospheric particle explorer (SAMPEX) mission', *IEEE Trans. Geosci. Rem. Sensing* **31**, 531–541.

Baring, M.G., Ogilvie, K.W., Ellison, D.C. and Forsythe, R.J.: 1997, 'Acceleration of solar wind ions by nearby interplanetary shocks: comparison of Monte Carlo simulations with Ulysses observations', *Astrophys. J.* **476**, 889–902.

Bieber, J.W., Burger, R.A. and Matthaeus, W.H.: 1995, 'The diffusion tensor throughout the heliosphere', *Proc. 24th Int. Cosmic Ray Conf. (Rome)* **4**, 694–697.

Biswas, S., Durgaprasad, N., Mitra, B. and Dutta, A.: 1993: 'Anuradha and low-energy cosmic rays', *Space Sci. Rev.* **62**, 3–65.

Bogdan, T.J., Lee, M.A. and Schneider, P.: 1991, 'Coupled quasi-linear wave damping and stochastic acceleration of pickup ions in the solar wind', *J. Geophys. Res.* **96**, 161–178.

Breneman, H.H. and Stone, E.C.: 1985, 'Solar coronal and photospheric abundances from solar energetic particle measurements', *Astrophys. J. Lett.* **299**, L57–L61.

Burlaga, L.F., Ness, N.F. and Belcher, J.W.: 1997, 'The radial evolution of corotating merged interaction regions and flows between $\approx$ 14 AU and $\approx$ 43 AU', *J. Geophys. Res.* **102**, 4661–4672.

Cook, W.R., Cummings, A.C., Cummings, J.R., Garrard, T.L., Kecman, B., Mewaldt, R.A., Selesnick, R.S., Stone, E.C. and von Rosenvinge, T.T.: 1993, 'MAST: a mass spectrometer telescope for studies of the isotopic composition of solar, anomalous, and galactic cosmic rays', *IEEE Trans. Geosci. Rem. Sensing* **31**, 557–564.

Cummings, A.C. and Stone, E.: 1988, 'Composition, gradients, and temporal variations of the anomalous cosmic-ray component', *Proc. 6th Int. Solar Wind Conf. (Boulder)* **306**, 599–614.

Cummings, A.C., Mewaldt, R.A., Blake, J.B., Cummings, J.R., Fränz, M., Hovestadt, D., Klecker, B., Mason, G.M., Mazur, J.E., Stone, E.C., von Rosenvinge, T.T. and Webber, W.R.: 1995, 'Anomalous cosmic ray oxygen gradients throughout the heliosphere', *Geophys. Res. Lett.* **22**, 341–344.

Cummings, A.C. and Stone, E.C.: 1996, 'Composition of anomalous cosmic rays and implications for the heliosphere', *Space Sci. Rev.* **78**, 117–128.

Cummings A.C. and Stone, E.C.: 1998, *Space Sci. Rev.*, this volume.

Decker, R.B., Krimigis, S.M. and Kane, M.: 1995, 'Spatial gradients, energy spectra, and anisotropies of ions $\gtrsim$ 30 keV at CIR shocks from 1 to 50 AU', *Proc. 24th Int. Cosmic Ray Conf. (Rome)* **4**, 421–424.

Earl, J.A.: 1974, 'A diffusive idealization of charged-particle transport in random magnetic fields', *Astrophys. J.* **193**, 231–242.

Ellison, D.C., Jones, F.C. and Eichler, D.: 1981, 'Monte Carlo simulation of collisionless shocks showing preferential acceleration of high A/Z particles', *J. Geophys. Res.* **50**, 110–113.

Ellison, D.C., Baring, M.G. and Jones, F.C.: 1996, 'Nonlinear particle acceleration in oblique shocks', *Astrophys. J.* **473**, 1029–1050.

Fisk, L.A., Kozlovsky, B. and Ramaty, R.: 1974, 'An interpretation of the observed oxygen and nitrogen enhancements in low-energy cosmic rays', *Astrophys. J. Lett.* **190**, L35–L37.

Geiss, J., Gloeckler, G. and von Steiger, R.: 1994, 'Solar and heliospheric processes from solar wind composition measurements', *Phil. Trans. Roy. Soc. London A* **349**, 213–226.

Geiss, J., Gloeckler, G., Mall, U., von Steiger, R., Galvin, A.B. and Ogilvie, K.W.: 1994, 'Interstellar oxygen, nitrogen, and neon in the heliosphere', *Astr. Astrophys.* **282**, 924–933.

Geiss, J., Gloeckler, G., Fisk, L.A. and von Steiger, R.: 1995, 'C^+ pickup ions in the heliosphere and their origin', *J. Geophys. Res.* **100**, 23,373–23,377.

Geiss, J., Gloeckler, G. and von Steiger, R.: 1996, 'Origin of C^+ ions in the heliosphere', *Space Sci. Rev.* **78**, 43–52.

Giacalone, J. and Jokipii, J.R.: 1996, 'Perpendicular transport in shock acceleration', *J. Geophys. Res.* **101**, 11,095–11,105.

Giacalone, J. and Jokipii, J.R.: 1997, 'Spatial variation of accelerated pickup ions at co-rotating interaction regions', submitted to *Geophys. Res. Lett.*

Giacalone, J., Jokipii, J.R., Decker, R.B., Krimigis, S.M., Scholer, M. and Kucharek, H.: 1997, 'The pre-acceleration of anomalous cosmic rays in the inner heliosphere', *Astrophys. J.* **486**, 471–476.

Isenberg, P.A.: 1987, 'Evolution of interstellar pickup ions in the solar wind', *J. Geophys. Res.* **92**, 1067–1073.

Jokipii, J.R.: 1987, 'Rate of energy gain and maximum energy in diffusive shock acceleration', *Astrophys. J.* **313**, 842–846.

Jokipii, J.R.: 1991, in G.P. Zank and T.K. Gaisser (ed.), 'Diffusive shock acceleration: acceleration rate, magnetic-field direction and the diffusive limit', *Particle Acceleration in Cosmic Plasmas*, Am. Inst. of Phys., College Park, Md., 137–147.

Jokipii, J.R.: 1992, 'Constraints on the acceleration of anomalous cosmic rays', *Astrophys. J. Lett.* **393**, L41–L43.

Jokipii, J.R., Kóta, J., Giacalone, J., Horbury, T.S. and Smith, E.J.: 1995, 'Interpretation and consequences of large-scale magnetic variances observed at high heliographic latitude', *Geophys. Res. Lett.* **22**, 3385–3388.

Jokipii, J.R.: 1996, 'Theory of multiply-charged anomalous cosmic rays', *Astrophys. J. Lett.* **466**, L47–L50.

Jokipii, J.R. and Giacalone, J.: 1998, *Space Sci Rev.,* this volume.

Klecker, B., Hovestadt, D., Scholer, M., Arbinger, H., Ertl, M., Kästle, H., Künneth, E., Laeverenz, P., Seidenschwang, E., Blake, J.B., Katz, N. and Mabry, D.: 1993, 'HILT: a heavy ion large area proportional counter telescope for solar and anomalous cosmic rays', *IEEE Trans. Geosci. Rem. Sensing* **31**, 542–548.

Klecker, B.: 1995, 'The anomalous component of cosmic rays in the 3-D heliosphere', *Space Sci. Rev.* **72**, 419–430.

Klecker, B., McNab, M.C., Blake, J.B., Hamilton, D.C., Hovestadt, D., Kästle, H., Looper, M.D., Mason, G.M., Mazur, J.E. and Scholer, M.: 1995, 'Charge states of anomalous cosmic-ray nitrogen, oxygen, and neon: SAMPEX observations', *Astrophys. J. Lett.* **442**, L69–L72.

Klecker, B., Oetliker, M., Blake, J.B., Hovestadt, D., Mason, G.M., Mazur, J.E. and McNab, M.C.: 1997, 'Multiply charged anomalous cosmic ray N, O, and Ne: observations with HILT/SAMPEX', *Proc. 25th Int. Cosmic Ray Conf. (Durban)* **2**, 273–276.

Le Roux, J.A., Potgieter, M.S. and Ptuskin, V.S.: 1996, 'A transport model for the diffusive shock acceleration of anomalous cosmic rays in the heliosphere', *J. Geophys. Res.* **101**, 4791–4803.

Lo, H.H., Kurzweg, L., Brackman, R.T. and Fite, W.L.: 1971, 'Electron capture and loss in collisions of heavy ions with atomic oxygen', *Phys. Rev. A* **4** **(4)**, 1462–1478.

Luhn, A., Klecker, B., Hovestadt, D., Gloeckler, G., Ipavich, F.M., Scholer, M., Fan, C.Y. and Fisk, L.A.: 1984, 'Ionic charge states of N, Ne, Mg, Si, and S in solar energetic particle events', *Adv. Space Res.* **4**, 161–164.

McDonald, F.B., Moraal, H., Reinecke, J.P.L., Lal, N. and McGuire, R.E.: 1992, 'The cosmic radiation in the heliosphere at successive solar minima', *J. Geophys. Res.* **97**, 1557–1570.

McKibben, R.B., Connell, J.J., Lopate, C., Simpson, J.A. and Zhang, M.: 1996, 'Observations of galactic cosmic rays and the anomalous helium during Ulysses passage from the south to the north solar pole', *Astron. Astrophys.* **316**, 547–554.

Mewaldt, R.A., Cummings, A.C., Cummings, J.R., Stone, E.C., Klecker, B., Hovestadt, D., Scholer, M., Mason, G.M., Mazur, J.E., Hamilton, D.C., von Rosenvinge, T.T. and Blake, J.B.: 1993, 'The return of the anomalous cosmic rays to 1 AU in 1992', *Geophys. Res. Lett.* **20**, 2263–2266.

Mewaldt, R.A., Cummings, J.R., Leske, R.A., Selesnick, R.S., Stone, E.C. and von Rosenvinge, T.T.: 1996a, 'A study of the composition and energy spectra of anomalous cosmic rays using the geomagnetic field', *Geophys. Res. Lett.* **23**, 617–620.

Mewaldt, R.A., Selesnick, R.S., Cummings, J.R., Stone, E.C. and von Rosenvinge, T.T.: 1996b, 'Evidence for multiply charged anomalous cosmic rays', *Astrophys. J. Lett.* **466**, L43–L46.

Miller, J.A. and Roberts, D.A.: 1995, 'Stochastic acceleration by cascading Alfvén waves in impulsive solar flares', *Astrophys. J.* **452**, 912–932.

Oetliker, M., Klecker, B., Hovestadt, D., Mason, G.M., Mazur, J.E., Leske, R.A., Mewaldt, R.A., Blake, J.B. and Looper, M.D.: 1997a, 'The ionic charge of solar energetic particles with energies of 0.3–70 MeV per nucleon', *Astrophys. J.* **477**, 495–501.

Oetliker, M., Klecker, B., Mason, G.M., McNab, M.C. and Blake, J.B.: 1997b, 'The abundance of anomalous cosmic ray carbon in the inner heliosphere', *Proc. 25th Int. Cosmic Ray Conf. (Durban)* **2**, 277–280.

Parker, E.N.: 1965 'The passage of energetic charged particles through interplanetary space', *Planet. Space Sci.* **13**, 9–49.

Pesses, M.E., Jokipii, J.R. and Eichler, D.: 1981, 'Cosmic ray drift, shock-wave acceleration, and the anomalous component of cosmic rays', *Astrophys. J. Lett.* **246**, L85–L88.

Reames, D.V., Barbier, L.M. and von Rosenvinge, T.T.: 1996, 'WIND/EPACT observations of anomalous cosmic rays,' *Adv. Space. Res.*, in press.

Reinecke, J.P.L., Moraal, H. and McDonald, F.B.: 1993, 'The cosmic radiation in the heliosphere at successive solar minima: steady state no-drift solutions of the transport equation', *J. Geophys. Res.* **98**, 9417–9431.

Reinecke, J.P.L., Moraal, H. and McDonald, F.B.: 1996, 'The cosmic radiation in the heliosphere at successive solar minima 3: steady state no-drift solutions of the transport equation', *J. Geophys. Res.* **101**, 21,581–21,588.

Schlickeiser, R.: 1989, 'Cosmic-ray transport and acceleration. I. Derivation of the kinetic equation and application to cosmic rays in static cold media', *Astrophys. J.* **336**, 243–263.

Selesnick, R.S., Cummings, A.C., Cummings, J.R., Mewaldt, R.A., Stone, E.C. and von Rosenvinge, T.T.: 1995, 'Geomagnetically trapped anomalous cosmic rays', *J. Geophys. Res.* **100**, 9503–9518.

Selesnick, R.S., Mewaldt, R.A. and Cummings, J.R.: 1997, 'Multiply charged anomalous cosmic rays above 15 MeV/nucleon', *Proc. 25th Int. Cosmic Ray Conf. (Durban)* **2**, 269–272.

Shafer, C.M., Gloeckler, G., Galvin, A.B., Ipavich, F.M., Geiss, J., von Steiger, R. and Ogilvie, K.: 1993, 'Sulfur abundances in the solar wind measured by SWICS on ULYSSES', *Adv. Space Res.* **13 (6)**, 79–82.

Simnett, G.M. and Roelof, E.C.: 1998, *Space Sci Rev.,* this volume.

Simpson, J.A.: 1995, 'The anomalous nuclear component in the three-dimensional heliosphere', *Adv. Space Res.* **16**, 135–149.

Smith, E.J., Balogh, A., Neugebauer, M. and McComas, D.: 1995, 'Ulysses observations of Alfvén waves in the southern and northern hemispheres', *Geophys. Res. Lett.* **22**, 3381–3384.

Spjeldvik, W.: 1979, 'Expected charge states of energetic ions in the magnetosphere', *Space Sci. Rev.* **23**, 499–538.

Steenberg, C.D. and Moraal, H.: 1996, 'An acceleration/modulation model for anomalous cosmic ray hydrogen in the heliosphere', *Astrophys. J.* **463**, 776–783.

Steenberg, C.D. and Moraal, H.: 1997, 'An alternative approach to the modeling of anomalous cosmic ray intensities in the heliosphere', *Adv. Space Res.*, accepted for publication.

Steenkamp, R. and Moraal, H.: 1993, 'Acceleration and modulation of anomalous helium and oxygen in 1977 and 1987', *Proc. 23rd Int. Cosmic Ray Conf. (Calgary)* **3**, 419–422.

Steenkamp, R.: 1995, 'Shock acceleration as source of the anomalous component of cosmic rays in the heliosphere', *Ph.D. Thesis*, Potchefstroom University for CHE, Potchefstroom, South Africa.

Stone, E.C., Cummings, A.C. and Webber, W.R.: 1996, 'The distance to the solar wind termination shock in 1993 and 1994 from observations of anomalous cosmic rays', *J. Geophys. Res.* **101**, 11,017–11,025.

Stone, E.C. and Cummings, A.C.: 1997, 'Evidence for anomalous cosmic ray S, Si, and Fe in the outer heliosphere and for a non-ACR source of S at 1 AU', *Proc. 25th Int. Cosmic Ray Conf. (Durban)* **2**, 289–292.

Takashima, T., Doke, T., Hayashi, T., Kikuchi, J., Kobayashi, M., Shirai, H., Takehana, N., Ehara, M., Yamada, Y., Yanagita, S., Hasebe, N., Kashiwagi, T., Kato, C., Munakata, K., Kohno, T., Kondoh, K., Murakami, H., Nakamoto, A., Yanagimachi, T., Reames, D.V. and von Rosenvinge, T.T.: 1997, 'The first observation of sulfur in anomalous cosmic rays by the GEOTAIL and the WIND spacecrafts', *Astrophys. J. Lett.* **477**, L111–L113.

Tappin, S.J. and Simnett, G.M.: 1996, 'Modulation of anomalous cosmic ray ions by the interplanetary medium', *Astrophys. J.* **469**, 402–411.

Trattner, K.J., Marsden, R.G., Bothmer, V., Sanderson, T.R., Wenzel, K.-P., Klecker, B. and Hovestadt, D.: 1996, 'Ulysses COSPIN/LET: latitudinal gradients of anomalous cosmic ray O, N and Ne', *Astron. Astrophys.* **316**, 519–527.

Vasyliunas, V.M. and Siscoe, G.L.: 1976, 'On the flux and the energy spectrum of interstellar ions in the solar system', *J. Geophys. Res.* **81**, 1247–1252.

Verma, M.K., Roberts, D.A., Goldstein, M.L., Ghosh, S. and Stribling, W.T.: 1996, 'A numerical study of the nonlinear cascade of energy in magnetohydrodynamic turbulence', *J. Geophys. Res.* **101**, 21,619–21,625.

Witte, M., Rosenbauer, H., Banaszkiewicz, M. and Fahr, H.: 1993, 'The Ulysses neutral gas experiment: determination of the velocity and temperature of the interstellar neutral helium', *Adv. Space Res.* **13**, 121–130.

Zhou, Y. and Matthaeus, W.H.: 1990, 'Models of inertial range spectra of interplanetary magnetohydrodynamic turbulence', *J. Geophys. Res.* **95**, 14,881–14,892.

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