THE ANOMALOUS COMPONENT OF COSMIC RAYS IN THE 3-D HELIOSPHERE

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Abstract More than 20 years ago, in 1972, anomalous flux increases of helium and heavy ions were discovered during solar quiet times. These flux increases in the energy range < 50 MeV/nucleon showed peculiar elemental abundances and energy spectra, e.g. a C/O ratio ≤ 0.1 around 10 MeV/nucleon, different from the abundances of solar energetic particles and galactic cosmic rays. Since then, this "anomalous" cosmic ray component (ACR) has been studied extensively and at least six elements have been found (He, N, O, Ne, Ar, C) whose energy spectra show anomalous increases above the quiet time solar and galactic energetic particle spectrum. There have been a number of models proposed to explain the ACR component. The presently most plausible theory for the origin of ACR ions identifies neutral interstellar gas as the source material. After penetration into the inner heliosphere, the neutral particles are ionized by solar UV radiation and by charge exchange reactions with the solar wind protons. After ionization, the now singly charged ions are picked up by the interplanetary magnetic field and are then convected with the solar wind to the outer solar system. There, the ions are accelerated to high energies, possibly at the solar wind termination shock, and then propagate back into the inner heliosphere. A unique prediction of this model is that ACR ions should be singly ionized. Meanwhile, several predictions of this model have been verified, e.g. low energy pick-up ions have been detected and the single charge of ACR ions in the energy range at ≈10 MeV/nucleon has been observed. However, some important aspects such as, for example, the importance of drift effects for the acceleration and propagation process and the location of the acceleration site are still under debate. In this paper the present status of experimental and theoretical results on the ACR component are reviewed and constraints on the acceleration process derived from the newly available ACR ionic charge measurements will be presented. Possible new constraints provided by correlative measurements at high and low latitudes during the upcoming solar pole passes of the ULYSSES spacecraft in 1994 and 1995 will be discussed.

1. Introduction

About 20 years ago anomalous flux increases in the low energy spectra of helium (< 50 MeV/nuc), oxygen, and nitrogen (< 20 MeV/nuc) were observed in near-Earth interplanetary space by several groups (Garzia-Munoz, Mason, and Simpson, 1973, Hovestadt et al, 1973, McDonald et al, 1974). The composition and energy spectra showed for instance a helium / proton ratio > 1 at 30 MeV/nucleon and carbon / oxygen ratio < 0.1 at 10 MeV/nuc, not compatible with solar and galactic cosmic ray abundances. Subsequently the elements neon (von Rosenvinge and McDonald, 1975, Klecker et al, 1977), Argon, and small amounts of carbon (C/O ≈1%, Cummings and Stone, 1987) have been detected in this "anomalous" cosmic ray (ACR) component. The apparent overabundance of elements with large first ionisation potential led to the

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hypothesis that the ACR component originates from interstellar neutral particles, penetrating into the inner heliosphere, being ionized by solar UV and by charge exchange with solar wind ions, convected into the outer heliosphere, and accelerated there to energies of 10 to ≈ 100 MeV/nuc. Being predominantly singly ionized, these ions would be much less modulated than galactic or solar cosmic rays of the same velocity and thus could be observed in the inner heliosphere (Fisk, Kozlovsky, and Ramaty, 1974). This model provided a qualitative explanation of the ACR component and much effort in the last 20 years was devoted to the quantitative modelling of the physical processes involved: (1) the penetration of interstellar neutrals into the heliosphere, (2) the ionization (pickup) of neutral particles in the solar wind, (3) losses due to charge exchange and adiabatic deceleration, (4) acceleration of pick-up ions from ≈ 4 keV/nuc to > 10 MeV/nuc, and (5) the modulation and propagation into the inner heliosphere. With the hypothesis of interstellar neutral particles being the source, the model also provided a crucial check, because ACR ions should be singly ionised.

2. Key Observations and their Implications

2.1 THE DETERMINATION OF THE IONIC CHARGE OF ACR IONS

The direct determination of the ionic charge in the energy range of tens of MeV/nucleon is still beyond the possibilities of current spacecraft experiments. However, a number of methods have been used over the last 20 years to infer the ionic charge of ACR ions. One method relies on arguments based on the rigidity dependence of the modulation in the heliosphere and uses rigidity dependent hystheresis effects or the shape of ACR spectra to infer the ACR ionic charge. It has been shown, for instance that observed phase lag effects were compatible with ACR helium being singly ionized (McKibben, 1977) and ACR oxygen having low charge states < 3 (Klecker et al., 1980). From the effect of modulation on the ACR energy spectra Cummings et al. (1984) inferred that ACR He, N, O, and Ne ions are singly ionized. Their finding was based on the assumption that the modulation depends on particle velocity and rigidity and that spectral features such as e.g. the flux maxima of different species show up at energies where the value of the diffusion coefficient is the same.

A different method with the advantage of not being dependent on propagation models in the heliosphere, has become available with ACR measurements onboard spacecraft in low altitude, high latitude orbits. This method utilizes the Earth's magnetic field as a magnetic spectrometer. The ionic charge can then be inferred from a comparison of the interplanetary ACR flux with the integrated low altitude flux (integral measurement) or by computing the trajectories of individual ions in the Earth's magnetic field (trajectory tracing method). From integral measurements of ACR oxygen onboard Skylab 3 Biswas et al. (1977) inferred that ACR oxygen is only partially ionized and recently Adams et al. (1991) derived a mean ionic charge $<Q> = 0.9$ (+0.3/-0.2). For a recent review see e.g. Biswas et al. (1993).

The trajectory tracing method was first applied to ACR measurements obtained with experiments onboard Spacelab 1 and Spacelab 3. Because of limited counting statistics the ionic charge could be derived for a few particles only, however, singly ionized oxygen (Oschlies et. al., 1989) and singly ionized O, N, and Ne (Singh et al., 1991, Dutta et al., 1993) were observed. Since the successful launch of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) in July 1992 (Baker et al., 1993) with its advanced instrumentation optimized for the observation of ACR ions (Klecker et al., 1993) the trajectory tracing method can now be applied for a large number of ACR ions. With the much improved accuracy in the determination of observation time, position, and direction of particles, SAMPEX also provides both much improved counting statistics and better accuracy for the ionic charge determination. Using SAMPEX data obtained in December 1992, it was shown by Klecker et al., (1993) that all oxygen, nitrogen, and neon ions in the energy range 8 - 28 MeV/nuc observed at $L < 3$ (≈ 100 particles) were singly ionized. In summary, there is good evidence now that the ACR component is singly charged. However, a small contribution of higher charge states cannot be excluded yet and needs further investigation.

2.2 INTERSTELLAR NEUTRALS AND PICKUP IONS

According to the model of Fisk, Kozlovsky, and Ramaty (1974), interstellar pickup ions are the seed particles for anomalous cosmic rays. Thus, the knowledge of the distribution of neutral particles and pickup ions in the heliosphere is highly important for the understanding of ACR ions. The major supply of neutral particles in the heliosphere is the local interstellar medium (LISM) which enters the heliosphere at a relative speed of about 25 km/s. Evidence of interstellar hydrogen and helium in the heliosphere was provided by measurements of resonantly scattered solar UV already before the discovery of the ACR component (Bertaux and Blamont, 1971, Thomas and Krassa, 1971) and the existence of pickup ions had been inferred from these measurements (e.g. Holzer, 1977, and references therein). More recently, interstellar neutral helium has been measured directly with advanced instrumentation on the Ulysses spacecraft (Witte et al., 1993). Pickup He^+ ions have been detected with the AMPTE / IRM spacecraft at 1 AU in 1985 (Möbius et al., 1985). Other pickup ions, namely H^+, N^+, O^+, and Ne^+ were only recently discovered on the Ulysses deep space probe (Gloeckler et al., 1993, Geiss et al., 1994). Another important question is whether the composition of pickup ions in the heliosphere is similar to the composition of the LISM. As pointed out by e.g. Fahr (1990, 1991), charge exchange reactions in the heliospheric interface plasma could significantly modify the composition of the neutral LISM species H, O, N, whereas neutral He and Ne would be much less affected. Recent results of atomic abundances derived from the measured pickup ion abundances by Geiss et al. (1994) indicate, however, that these changes are small and very likely less than a factor of two as can be seen from He/O abundance in Fig 1. Another important recent finding from Ulysses is the observed acceleration of pickup H^+ and He^+, as well as of solar wind particles at the passage of a corotating interaction region (Gloeckler et al., 1994). These measurements are interesting in two respects: (1) they provide new insight into the injection process and (2) they show that a pre-accelerated component with energies of ≈ 100 keV/nuc may be available in the outer heliosphere for the acceleration to ACR energies.

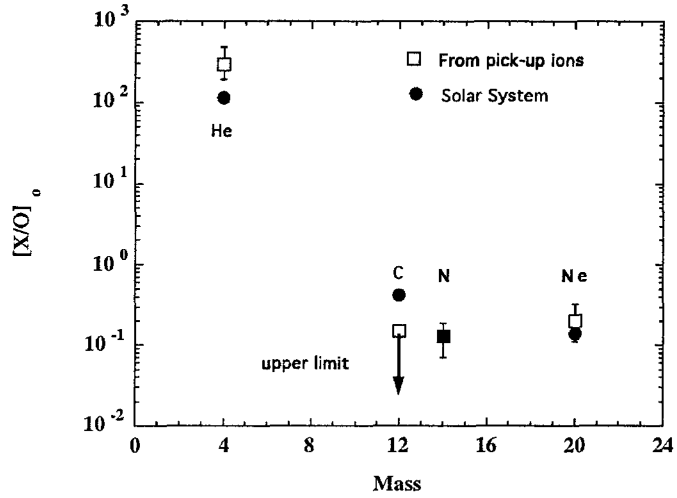

Fig. 1 Atomic abundances relative to oxygen derived from pickup ion observations (from Geiss et al., 1994), and solar system abundances from Anders and Grevesse, 1988.

2.3 LONG-TERM MODULATION

Measurements over the last two solar cycles showed that the anomalous component is especially sensitive to solar modulation. The flux of ACR oxygen at ≈ 10 MeV/nuc in the inner heliosphere varied for instance by a factor ≥ 100 and was observable at 1 AU only for solar minimum conditions. The maximum intensity shows a pronounced asymmetry in consecutive solar cycles, similar to the time profiles of galactic cosmic rays, indicative of the importance of the direction of the solar magnetic field, i.e. the importance of drift effects for the propagation in the heliosphere (Mewaldt et al., 1993).

2.4 COMPOSITION AND ENERGY SPECTRA

In addition to ACR He, O, N, and Ne discovered in the inner heliosphere, measurements in the outer heliosphere showed that also Ar and, to a much lesser extent, C (≈ 1%) exhibit anomalous flux increases above the galactic cosmic ray spectrum (Cummings and Stone, 1987). Possibly H has also been detected (Christian, Cummings and Stone, 1988). However, the decomposition of the observed H spectrum into an ACR and GCR component depends highly on the assumed GCR spectrum, and, as pointed out by McDonald et al. (1992), reduced adiabatic energy losses in the outer heliosphere might also account for the observations.

The energy spectra of ACR ions, after correction for solar and galactic cosmic ray contributions, exhibit a characteristic maximum, scaling with the mass of the ion (Cummings and Stone, 1987). The energy of the flux maximum depends on the acceleration and modulation processes and thus provides a sensitive boundary condition for the models. Significant (factor ≈ 2) differences of the energy of the flux maximum were reported for the ACR oxygen spectrum in 1985/1986 when compared with ACR fluxes during the previous solar minimum (Cummings and Stone, 1986, see also discussion in Fisk, 1986) However, subsequent measurements reported by Cummings and Stone (1990) show that these differences of the ACR oxygen spectra are much smaller for the actual solar minimum conditions reached in 1987. Only a very small shift of ≈ 30% of the energy of the flux maxima was also observed in 1987 for ACR helium (McDonald et al., 1992).

2.5 RADIAL AND LATITUDINAL GRADIENTS

The radial and latitudinal gradients also place important constraints on the acceleration and propagation models of ACR ions in the heliosphere. A parameter particularly sensitive to the model calculations is the latitude gradient. If drift effects are important then the latitude gradient is predicted to change sign in two consecutive solar cycles, i.e. with the reversal of the polarity of the solar magnetic field. This sign reversal was observed, indeed, in the last two solar cycles as shown in Fig. 2 (McKibben, 1989, Cummings et al., 1987). Radial and latitudinal gradients and new results obtained with experiments

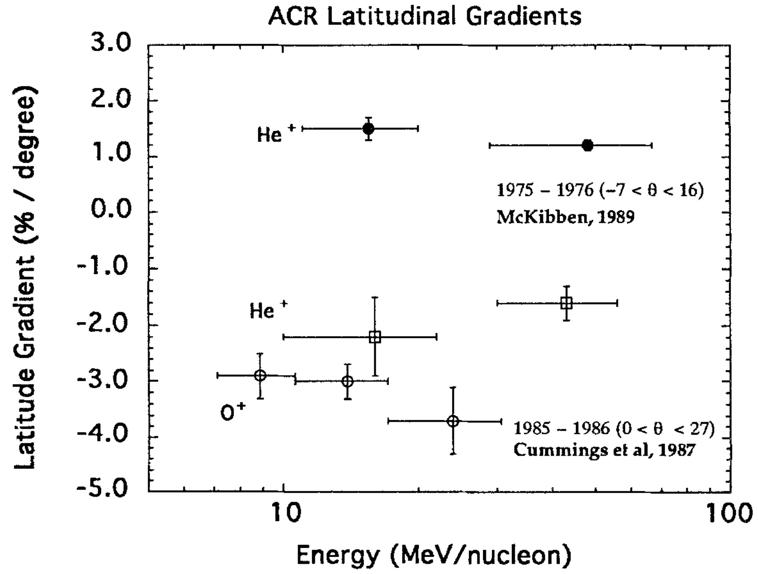

Fig 2 Latitudinal gradients in two consecutive solar cycles with different magnetic field polarity.

onboard the Ulysses spacecraft at latitudes < 60° are discussed in detail in another paper of this volume (McKibben, 1994). These results indicate that the latitudinal gradient in the present solar cycle so far is very small (≈ 1% per degree) and positive, in qualitative agreement with the model predictions. It will be very interesting to see the latitudinal gradient in the upcoming solar pole passes of the Ulysses spacraft in 1994 and 1995.

3. Acceleration and Modulation of ACR Ions

With the detection of pickup He, O, N, and Ne between 1 and 5 AU the seed particle population of ACR ions has been identified. The measured pickup energy distribution exhibits a typical cut-off at twice the solar wind velocity (Möbius et al., 1985, Gloeckler et al., 1993), thus the pickup ions need to be accelerated from ≈ 4 kev/nuc by a factor > 1000 to account for the observed energy of ACR ions. Whereas the origin of the ACR component now appears to be reasonably well established, the location of the acceleration site and the acceleration mechanism are still under debate. The observational constraints, i.e. the positive radial gradient observed out to ≈ 40 AU and the correlation of the modulation with the modulation of GCR, place the acceleration region into the outer heliosphere. So far essentially three theories have been developed for the acceleration of the anomalous component.

3.1 TRANSIT-TIME DAMPING

Acceleration by large scale magnitude fluctuations of the magnetic field in the outer heliosphere, generated by e.g. stream-stream interaction regions in the azimuthal field configuration of the low latitude solar wind has been proposed by Fisk (1976a). Using the magnitude and spectrum of these fluctuations as free parameters Klecker (1977) was able to reproduce the intensity and spectra of ACR oxygen, nitrogen, and neon reasonably well in a spherically symmetric, steady state model for the acceleration and modulation. However, whether the interaction of ACR ions with these fluctuations can be approximated by a linear theory is not completely clear (see also discussion in Fisk, 1986). With the deep space probes coming closer to the termination shock an experimental test may become available, because the energy spectra expected from transit-time damping (see e.g. Fisk, 1976b, Klecker, 1977) would not show the power law energy dependence at low energies as predicted by diffusive shock acceleration discussed below.

3.2 ACCELERATION AT THE TERMINATION SHOCK OVER THE SOLAR POLES

A qualitative model for the acceleration of ACR ions at the quasi-parallel termination shock over the solar poles, including also the effects of gradient and curvature drifts, was proposed by Pesses, Jokipii, and Eichler (1981). Particles can be accelerated at this shock by being scattered back and forth across the shock front, and gain energy by the converging solar wind flow (diffusive shock acceleration, also called the first-order Fermi mechanism), much as it occurs at interplanetary shocks or at the Earth's bow shock. A quantitative model of this acceleration process, including the effects of diffusion, convection, adiabatic deceleration, and drift and assuming particle injection at small polar angles was presented by Jokipii (1986). An important result of the drift models is the prediction of a 22 year cycle which apparently is observed for the modulation and latitudinal gradient as discussed above. The spectral differences in two consecutive solar cycles as initially predicted by the model can qualitatively be understood from the drift path of positive ions: for time periods with the solar magnetic field pointing outward in the northern hemisphere ($qA>0$, 1972 - 1975 solar minimum) positive ions injected near the poles spend considerably less time near the termination shock than during time periods with $qA<0$ (1987 solar minimum), when these particles drift to larger values of the polar angle when they gain energy. However, as the results for solar minimum conditions in 1987 show, the measurements now indicate that the spectral differences are small. This could be due to drift effects being less important or due to the assumption on the injection region. However, it could also be due to the polar magnetic field configuration: if the polar magnetic field is significantly larger than the nominal Archimedian spiral field as proposed by Jokipii and Kota (1989), drift effects would be reduced considerably and the spectral differences would be reduced by about an order of magnitude (Jokipii, 1990).

3.2 ACCELERATION AT THE TERMINATION SHOCK IN THE ECLIPTIC

Acceleration at the quasi-perpendicular termination shock near the equatorial plane has been suggested by Fisk (1986). In this nearly azimuthal field configuration there is a potential problem with the injection as also pointed out by Pesses et al. (1981): for the diffusive acceleration process to work, the injected particles have to travel back upstream. However, large directional fluctuations of the on average nearly azimuthal field have been observed with the Pioneer 11 spacecraft at distances of ≈ 32 AU (Smith, 1993). Using the width of the measured distribution ($\Phi_{FWHM} \approx 35°$) and assuming that the distribution will be similar near the termination shock, the percentage of time when the angle between the magnetic field direction and the shock normal (Θ_{BN}) is e.g. less than 70°, is $\approx 20\%$, i.e. injection at the equatorial plane seems not to be a problem. In fact, the injection may take place at all polar angles.

In the next paragraph time scales for different acceleration and loss processes will be investigated in order to obtain constraints for the acceleration mechanism and acceleration site.

4. Time Scales for Acceleration and Loss Processes

As pointed out by Jokipii (1992), the time scales of loss processes acting on ACR ions in the outer heliosphere impose severe observational constraints on possible acceleration mechanisms. Relevant loss processes are (1) losses due to charge exchange reactions and (2) energy loss due to adiabatic deceleration. The loss time scales τ_{loss} can be compared with acceleration time scales τ_{acc} and only mechanisms with $\tau_{acc} < \tau_{loss}$ will provide efficient acceleration. The present estimates for the distance of the termination shock range from ≈ 60 to ≈ 90 AU (Potgieter, 1993), therefore for the following estimate of acceleration and loss time scales a termination shock distance of 80 AU will be assumed.

4.1 LOSS TIME SCALES

Losses by charge exchange reactions of O^+ ($O^+ \dashrightarrow O^{n+}$) in the local interstellar medium have been investigated by Adams and Leising (1991). Using a local interstellar neutral hydrogen density of $n_H = 0.1 / cm^3$ and an upper limit of $<Q> < 1.6$ for the mean charge state of oxygen as reported by Adams et al. (1990), they inferred a maximum propagation distance d_{max} of 0.2 pc for O^+ ions at 10 MeV/nuc and concluded from this result that the ACR source must be local. Applying this maximum propagation distance to the outer heliosphere, it can be converted to a loss time scale of $\tau_{loss} = d_{max} / v = 4.6$ years.

At low energies (< 0.1 MeV/nuc), the dominant loss process is charge pick-up. With typical values of $\lambda_{ec} \approx 10^{-16}$ cm^2 (e.g. Spjeldvik, 1979) for the electron capture cross section of O^+ at 0.1 MeV/nuc and $n_H = 0.1 / cm^3$ we obtain $\tau_{loss} = 1 / (v \lambda_{ec} n_H) =$ 0.73 years.

With particle momentum p, heliospheric radial distance r and solar wind velocity V_{SW}, the time scale for adiabatic deceleration is $\tau_{ad} = (1/p\ dp/dt)^{-1} = 3r / 2V_{SW}$. Using 350 km/s as an average solar wind velocity, this results in $\tau_{ad} = 1.63$ y at 80 AU. Note, that near the termination shock the energy loss rate may be reduced because particles are alternating between the upstream and downstream region, as pointed out by Jokipii (1992).

4.2 ACCELERATION TIME SCALES

In the following paragraph we will compare the loss time scales derived above with acceleration time scales for the first- and second order Fermi process and transit-time damping.

The second order Fermi acceleration is generally slow , it scales as $\tau_{F2} \approx 2\kappa / V_A^2$ (e.g. Ip and Axford, 1986), where κ is the diffusion coefficient and V_A the Alfvén velocity. A lower limit for the acceleration time can be obtained by using the Bohm limit (κ_B) for the diffusion coefficient, $\kappa_B = v\, r_g / 3$), with particle velocity, v, and particle gyroradius r_g. For the following discussion a nominal Archimedian spiral magnetic field configuration is assumed with typical solar wind and magnetic field parameters at 1 AU ($v_A = 50$ km/s, $B = 5$ nT, $V_{SW} = 350$ km/s). The resulting acceleration times for 10 MeV/nuc O^+ at 80 AU and 0° and > 80° latitudes are 60 and > 300 years, respectively. It is evident from this result that the acceleration time scale for second order Fermi acceleration is much too long to account for the observed energies.

The acceleration rate for transit-time damping (τ_{ttd}) depends on the correlation lengths scales, on the magnitude fluctuations of the magnetic field ($\eta = \langle(\delta B)^2\rangle / B_o^2$) and on the power spectrum index , q, of the fluctuations, and scales approximately as $\tau_{ttd} \approx \eta\ v\ r_g^{q-2}$, provided the gyroradia are small compared to the correlation lengths of the fluctuations. (Fisk, 1976a, Klecker, 1977). Typical values obtained for the acceleration rate of He^+ at 10 MeV/nuc and 50 AU using $\eta=0.1$, and typical solar wind parameters are $2*10^{-8}$ sec^{-1} (Fisk, 1976a, Klecker, 1977). Using the simple scaling law given above, this value corresponds for q=1 to an acceleration rate of $5*10^{-9}$ sec^{-1} for O^+ at 10 MeV/nuc, i.e. to an acceleration time scale $\tau_{ttd} \approx 3$ years . This is somewhat larger than the time scale for adiabatic energy losses and comparable with charge exchange losses (see also Fig 3). However, considering that this statistical acceleration also results in considerable energy spreading, transit-time damping cannot be excluded on the basis of the constraints posed by the loss processes discussed.

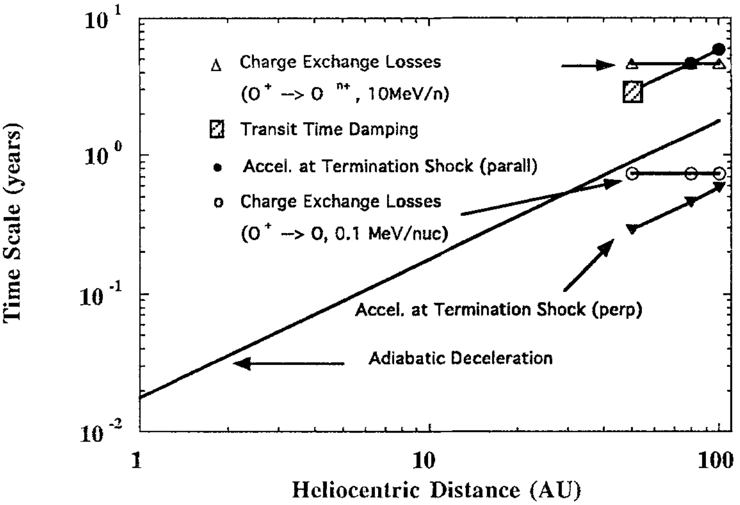

Fig. 3 Acceleration and loss time scales at 0° latitude in the outer heliosphere, for details see paragraph 4.

The acceleration time scales for first order Fermi acceleration (τ_{F1}) at parallel and perpendicular shocks have been reviewed by Jokipii (1987) and were subsequently used by Jokipii (1992) for an estimate of the acceleration time scales of ACR oxygen. Using again the Bohm limit for the diffusion coefficient, a lower limit of the acceleration time scale at a quasi-parallel shock is given by : $\tau_{F1||} = 2\ r\ /\ (r-1)\ v\ r_g\ /\ V_{sh}^2$ (Jokipii, 1992), where r is the shock compression ratio and V_{sh} the shock velocity. This time scale is plotted in Fig. 3 for 10 MeV/nuc O^+ and 0° latitude as a function of heliocentric distance and in Fig 4 as a function of latitude at 80 AU. In order to approximate the influence of the high solar wind velocity in the polar coronal holes a linear increase of the solar wind velocity from 350 km/s at 45° to 700 km/s at 90° latitude has been assumed in Fig. 4. Considering that these values of $\tau_{F1\|}$ are a lower limit and that at low latitudes quasi-parallel conditions will only exist for a small fraction of the time, diffusive shock acceleration seems to be too slow to compete with the losses at 10 MeV/nuc. However, with $\tau_{F1\|} \approx v\, r_g$ the acceleration time scale for 0.1 MeV/nuc O^+ is a factor of ≈ 100 smaller than the values shown in Fig. 3 and 4, i.e. the charge exchange loss time scale of 0.73 years at 0.1 MeV/nuc does not seem to pose a serious problem.

Much smaller time scales can be obtained for acceleration by a quasi-perpendicular shock, because here κ_{perp} is more relevant than $\kappa_\|$ and κ_{perp} is not limited by the gyroradius. The acceleration time scales $\tau_{F1,perp}$ obtained with typical values of κ as used in modulation model calculations ($k_\| = 5\ 10^{21}\ R^{0.5}\ \beta\ B_E/B$ and $k_{perp} = 0.03 * k_\|$, Jokipii, 1992) is also shown in Fig. 3 and Fig. 4. These time scales are considerably smaller than the loss time scales , i.e. diffusive shock acceleration at a perpendicular shock would satisfy the observational constraints for a large range of latitudes.

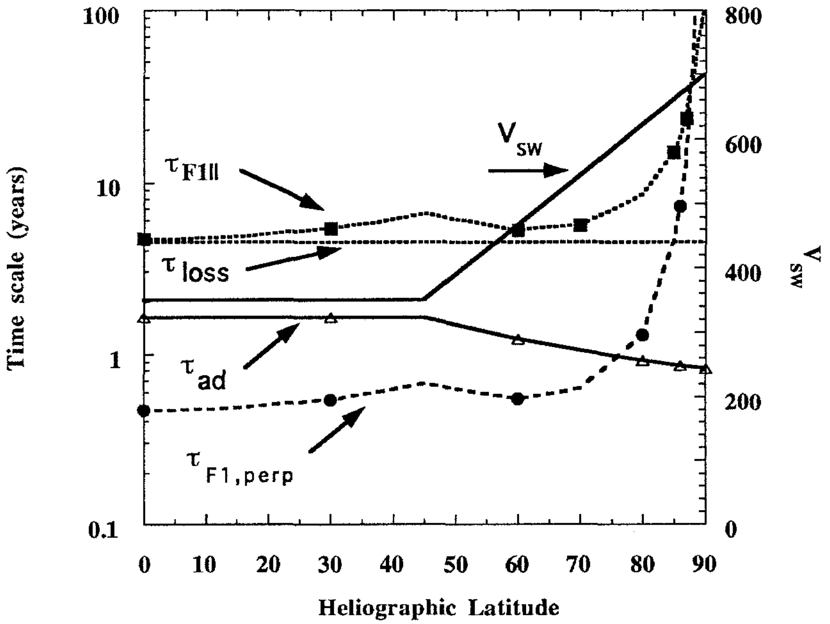

Fig. 4 Time scales for acceleration and loss processes at 80 AU, for details see paragraph 4.

5. Summary

There is now compelling evidence that the source of the anomalous component of cosmic rays is indeed interstellar neutrals, ionized and accelerated in the heliosphere as already proposed 20 years ago. In particular, the ionic charge of ACR ions at $\approx$ 10 to 30 MeV/nuc has been determined and singly charged O, N, Ne have been unambiguously identified. In addition to interstellar pickup He^+, the pickup ions H^+, O^+, N^+, and Ne^+ have been detected with the novel plasma composition experiments onboard the Ulysses spacecraft. This enables us now to measure the seed population of ACR ions directly.

Much less clear is the question of the acceleration mechanism and the acceleration site. Comparing acceleration and loss time scales it is evident that a second order Fermi process is too inefficient to compete with charge exchange losses and energy loss by adiabatic deceleration. Transit-time damping at low latitudes cannot be ruled out, however, it remains still to be shown that the magnitude fluctuations of the magnetic field do have the required fluctuation levels and scale sizes. Acceleration at a quasi-parallel shock at high latitudes as originally proposed does not have the required small acceleration time scale if a nominal Archimedian spiral field is assumed. However, an increased polar field as also discussed in connection with propagation models could change this result significantly. The shortest acceleration times are obtained with diffusive shock acceleration at a quasi-perpendicular shock. In fact, this acceleration time scale satisfies the constraints imposed by the loss processes over a large range of latitudes.

So far Ulysses provided already important new results on the seed particle population of ACR ions. The comparison of ACR fluxes and energy spectra obtained during the polar passes of Ulysses in 1994 and 1995 with the data from near-Earth and interplanetary spacecraft can be expected to provide a new and unique opportunity for the test of the acceleration site, the acceleration mechanism and the propagation of the anomalous component in the heliosphere.

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