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The Modulation of Anomalous Helium During an qA>0 Minimum Modulation Period

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Abstract

During the qA>0 solar minimum modulation period (SMMP) of 1977 anomalous helium spectra were measured at distances of 1, 1.8, 6 and 15 AU and again during the qA>0 SMMP of 1997 at distances of 1, 52 and 65 AU from earth by various spacecraft. If the solar modulation cycle is a true 22 year cycle one should be able to treat these measurements as if they were made during the same qA>0 SMMP. In this contribution difficulties encountered with anomalous helium during such an approach are described.

1 Introduction

The Pioneer 10 and 11, Voyager 1 and 2, and IMP 8 spacecraft have, during the last three consecutive solar minimum modulation periods of 1977, 1987 and 1997, measured anomalous and galactic cosmic ray particle spectra at radial distances from 1 AU to 66 AU from the sun. For the first time, one is now in possession of particle spectra measured at various distances from the sun during two consecutive SMMP's of the same polarity, namely those of 1977 and 1997. These data have been compiled and reviewed in several papers by McDonald and his co-workers [e.g., McDonald et al., 1998, and references therein].

In this paper we will concentrate on one of the particle species for which the most extensive set of spectra were measured during the qA>0 SMMP's of 1977 and 1997, namely anomalous helium. If the solar modulation cycle is truly a 22 year cycle, one would expect similar modulation conditions during these two periods, and one should be able to treat the spectra measured during these two periods as if they were measured at the various distances from the sun during the same modulation period. With our no-drift and drift models we will explore to what extent this assumption is true, that is to what extent one can simulate the 1977 and 1997 anomalous hydrogen spectra with a single diffusion tensor. In paper SH 3.1.19 we show that we are able to simulate galactic hydrogen spectra measured during these two periods successfully with a single radial diffusion mean free path.

For details of our approach in recent model simulations and for details of the modulation models used, the reader is referred to our paper SH 3.1.19 in this proceedings.

2 Modulation of Anomalous Cosmic Rays

It is now generally accepted that the anomalous component of cosmic rays (ACR) consists of locally ionized particles which are accelerated at the solar wind termination shock (SWTS). To study the modulation of these particles one should ideally employ a model which includes a discontinuous shock transition in the solar wind speed in the heliosphere and in which the spectrum of the anomalous species to be modulated is generated in a self-consistent manner at this shock. Such a two-dimensional model as the one developed by Steenkamp [1995] is, unfortunately, very time-consuming because it has to be time-dependent for technical reasons. Searches of the parameter space with such a model is not a practical proposition.

If the spectrum on the SWTS is known, a simple steady-state solution of the transport equation (TPE) describes the modulated intensities inside the SWTS. These steady-state models are numerically very stable, requiring approximately 50 seconds to obtain a solution, and therefore serve as a very useful approximation of the full time-asymptotic solution. In his recent Ph.D.-thesis Steenberg [1998] showed that the no-drift time-asymptotic spectrum for ACR's on the SWTS can be written in terms of an elementary formula, the coefficients of which contain the physical propagation and acceleration parameters. In this paper this parameterized spectrum on the SWTS is used as "input" for a steady-state model to study the modulation of ACR helium. Steenkamp [1995] has already shown that modulation between the SWTS and the modulation boundary has a negligible effect on the modulated spectra inside the SWTS so one needs not be concerned about what happens between these two boundaries.

For a thorough discussion of the parameterized shock spectrum the reader is referred to Chapter 6 of Steenberg's thesis. The spectrum on the SWTS is given by

$$j_T = Q_J\, x^{1-q/2} \exp(-bx^a) \qquad (1)$$

where j_T ($\propto P^2 f$) is the particle intensity, Q_J a normalization factor determined by the source of particles injected into the shock, and $q = 3s/(s-1)$, with s the compression ratio of the shock. In this paper the same value of Q_J was used for all the model calculations. Finally, $x = T/T_c$, with T_c the curvature cutoff energy of the first order Fermi acceleration, where the diffusive length scale, k_{rr}/V, becomes of the same order of magnitude as the dimensions of the system, r_s. V is the solar wind speed, r_s the radial distance from the sun to the SWTS and κ_{rr} the radial diffusion coefficient. Steenberg showed that the cutoff occurs at an energy T_c where Vr_s/k_{rr} » 10. This implies that the cutoff occurs at a much lower energy than is generally assumed.

The parameters a and b in (1) are given in terms of the rigidity dependence of the diffusion mean free path:

$$a = 0.689\, g + 1.34 \qquad (2a)$$

$$b = -\ 0.083\, g + 0.272. \qquad (2b)$$

If the radial mean free path is written as

$$l_{rr} = l_{rro}\, g(r)\, (P/P_o)^{\gamma} \qquad (3)$$

with P_o = 1 GV, the cutoff energy is, in the non-relativistic limit ($T_c << E_o$), which is applicable for all ACR calculations, given by

$$T_C = 0.5 \times [(0.3 V r_s / c\, l_{rrs})^2\, E_0^{1-g} (Z/A)^{2\gamma}\,]^{1/\gamma+1} \qquad (4)$$

With E_o = 0.938 GeV, T_c is expressed in GeV/nucleon. Note that $l_{rrs} = l_{rro}\, g(r_s)$ is the value of the spatial part of l_{rr} at the SWTS.

We have found that the value of γ used in calculating input spectra at the SWTS does not have a significant effect on the quality of the data fits calculated with these input spectra. To limit the model space we calculated all input spectra at the SWTS with $\gamma = 1$.

Frame A shows a solution of the TPE calculated for singly charged anomalous He^+ (Z = 1, A = 4) using (1) as input spectrum for a strong shock (s = 4) at r_s = 90 AU, and with $l_{rr} = 0.5\,(P/P_o)$ AU, i.e. with $\gamma = 1$ in equations (2). This input spectrum is shown by the solid curve. The vertical line shows the cutoff energy at T_c = 9 MeV/nucleon. Below this energy the slope of the spectrum is $(1-q/2) = -1$, because $q = s = 4$. The broken line curves show modulated spectra at 1, 20, 40, 60, and 80 AU in the ecliptic plane where the solar wind speed is 400 km/s. These spectra are multiplied by factors of 10. The model is one-dimensional, i.e. $l_{qq} = 0$. The normalization constant has the value Q_J = 109 particles/m^2/sr/s/MeV/nucleon, and this value is kept constant throughout this paper.

This solution demonstrates an important fundamental behavior of the modulation of the anomalous component, namely that the positions of the peaks of the modulated spectra occurs within 50% of the cutoff energy. Careful inspection show that the positions of the peaks of the modulated spectra shift towards higher energies as one moves from the SWTS towards Earth. This is what one would expect if diffusion was the only modulating process. Adiabatic energy losses however have an opposite effect on peak positions in the inner heliosphere, causing them to shift towards lower energies. The net effect is that peak positions occur at approximately the same energy throughout a large part of the heliosphere.

3 Results and discussion

3.1 Positions of the peaks in the measured and calculated spectra: Anomalous helium spectra measured at 1, 1.8, 6 and 15 AU during 1977, the 1987 spectra measured at 24, 31 (34^o N) and 42 AU and the 1997 spectra measured at 1, 51.5 (21^o S) and 65.5 (34^o N) AU are plotted in Frame B. The vertical dimension of the data symbols represents a variation of approximately 15%. The actual values of the data are plotted at 1 AU, but at the other distances the spectra were multiplied by factors of 10. The solid lines in Frame B are exactly the same no-drift model solutions as in Frame A, but now calculated for the appropriate distances. The normalization constant Q_J in equation (1) was chosen as Q_J = 109 particles/m^2/sr/s/MeV/nucleon to give the "best overall fit" to the data in Frame B.

We note from Frame B that

1. the positions of the peaks of the measured spectra differ for the three solar minimum periods under discussion with the 1997 peaks in the outer heliosphere at approximately 6 – 7 MeV/nuc while the 1977 maxima occurred at approximately 15 – 20 MeV/nuc and the 1987 maxima at a slightly higher energy than the 1977 maxima;
2. the 1977 and 1997 Imp8-spectra at 1 AU coincide very well;
3. the peaks of the spectra measured during 1977 and 1987 shift towards slightly lower energies with increasing radial distance in each period while the peaks of the calculated spectra shift in the opposite direction for radial distances smaller than 50 AU.

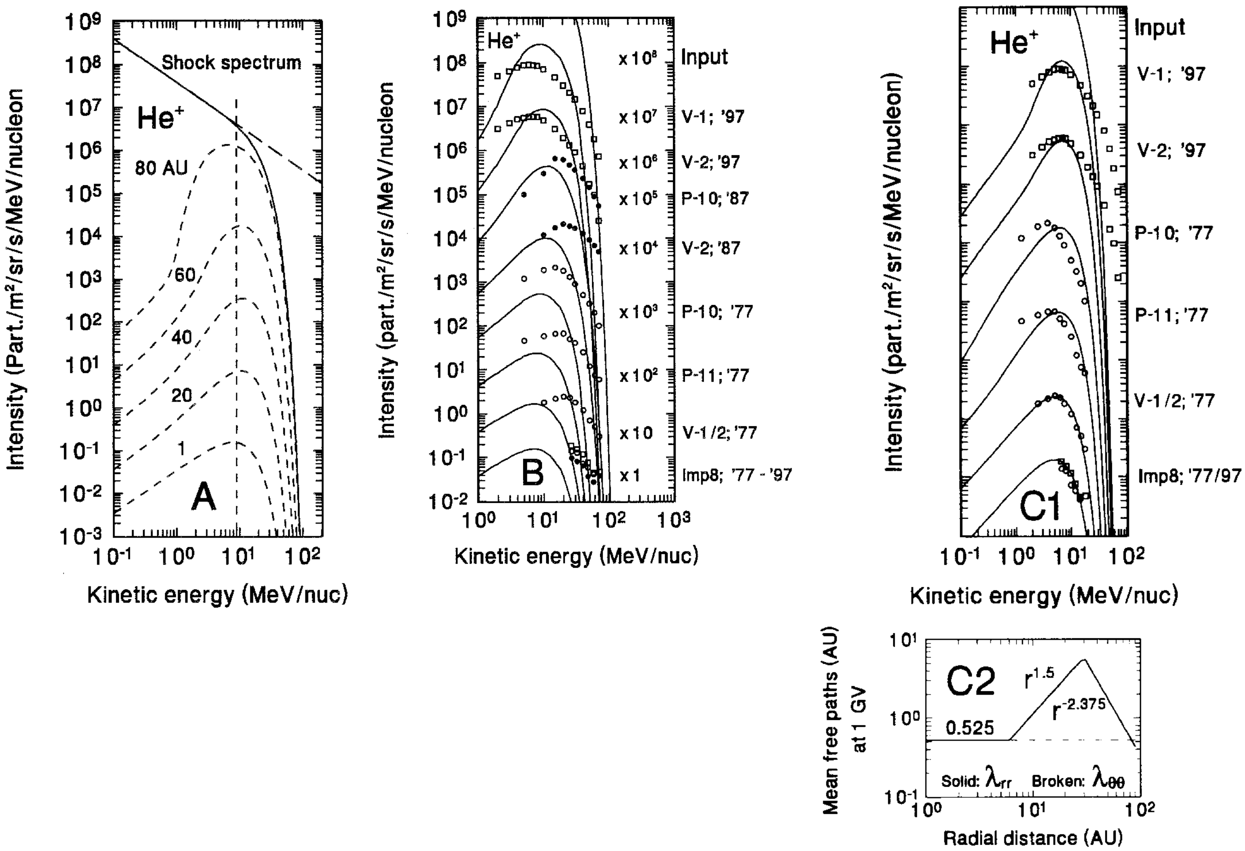
It is clear from expression (4) that for the case $\gamma = 1$ (that is l_{rr} μ P/P_o) the position of the cutoff in the shock spectrum, and therefore the positions of the peaks of the modulated spectra, are inversely proportional to l_{rrs}, the value of the spatial part of the radial diffusion mean free path (RMFP) at the position of the shock. We found that to simulate the peak positions for the 1977 spectra approximately correct, l_{rrs} has to be equal to 0.2 AU and for the 1997 peaks in the outer heliosphere its value has to be four times larger, namely 0.8 AU.

The fact that l_{rrs} has to be smaller for the 1977 peaks than for the 1997 peaks, tempts one to suggest that conditions at the 1977 SWTS were more turbulent than at the 1997 SWTS. Such a conclusion will however not be in agreement with the fact that the 1977 and 1997 IMP8 spectra at 1 AU coincide to a large extent. One may also suspect that the inability of the model to reproduce the 1997 peak positions is a result of the very steep input spectrum at the SWTS, shown in Frame B. We tried a number of "less steep" forms for the input spectrum on the SWTS and found that it did not remedy the problem. Even for a very flat input spectrum at the SWTS our model predicts the positions of the peaks in the modulated spectra at 10 and 60 AU at approximately the same energy. Thus our model cannot at the present time explain the significant difference between the peak positions of the 1997 spectra in the outer heliosphere and those of the 1977 spectra in the inner heliosphere. We also have no explanation for the opposite radial dependence of the peak positions of the measured and calculated spectra at radial distances smaller than 50 AU.

3.2 A single RMFP?: It is clear from the previous paragraph that our effort to simulate the 1977 and 1997 anomalous helium measurements with one set of modulation parameters is frustrated, because it is not possible to simulate the positions of the peaks of the modulated spectra for the two periods with the same value of the RMFP at the shock. This is in sharp contrast with the galactic hydrogen case described in paper SH 3.1.19 of this conference.

The fact that the peak positions for the 1977 spectra were simulated approximately correct with l_{rrs} = 0.2 (P/P_o) AU while for the 1997 peaks in the outer heliosphere the value of l_{rrs} has to be four times larger, namely 0.8 (P/P_o) AU, prompted us to (i) shift the 1997 measurements at large radial distances to higher energies by a factor 4.0 and employ the l_{rrs} = 0.2 (P/P_o) AU-shock spectrum to calculate "modulated spectra" at the different radial distances, or (ii) shift the 1977 measurements (and the 1997 measurement at 1 AU) to lower energies by a factor 4.0 and employ the l_{rrs} = 0.8 (P/P_o) AU -shock spectrum to calculate "modulated spectra" at the different radial distances.

The "modulated spectra" calculated for case (ii) are shown in Frame C1. The RMFP l_{rr} is proportional to P and l_{rr} and l_{qq} have the radial dependencies shown in Frame C2. The reader should note that the model is not one-dimensional anymore. Except for the "peak positions" at P-10 and P-11 in 1977 the "fits to the data" are rather good. For case (i) almost identical "data fits" were calculated with a l_{rr} that is a factor 4 smaller than for case (ii), and with both l_{rr} and l_{qq} having the same spatial dependencies as in Frame C2. We have shown that the l_{rr} used in case (ii) also yields reasonably good fits to the galactic helium spectra measured for these two periods whilst the l_{rr} used in case (i) did not fit the galactic data at all. Very similar results were obtained with a drift model. The measured galactic helium spectra were reasonably well fitted with the same l_{rr} that "fitted" the anomalous helium "spectra" in the case (ii)-scenario above.



4. Conclusions

Our model can not with a single l_{rr} simultaneously reproduce the positions of the peaks of anomalous helium spectra measured during 1977 in the inner heliosphere and those measured during 1997 in the outer heliosphere. Independent of the steepness of the input spectrum at the SWTS, our model predicts the positions of the peaks in the modulated spectra at 10 and 60 AU at approximately the same energy. An interesting result is that if one shifts the 1977 ACR helium spectra in the inner heliosphere and the 1997 ACR helium measurement at 1 AU to the left on the energy axis by a factor 4.0, one can simulate the resulting "spectra" with the same l_{rr} that gives a good simultaneous fit to the galactic helium spectra measured during 1977 and 1997. It is not clear to us what the physical significance of this result is.

References

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