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On the timescale and location of ^{3}He acceleration

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ABSTRACT

We present a novel explanation for the ^{3}He-rich solar energetic particle events. We suggest that at low latitudes the coronal magnetic field is largely closed out to several solar radii. Quasi-continuous magnetic reconnection provides conditions suitable for resonant acceleration of ^{3}He which essentially accelerates all the ambient ions up to energies around 1 MeV/nucleon, which are largely trapped in the closed field. Electrons are also accelerated together with a relatively small number of ions which also satisfy the resonance condition. Ultra-heavy ions may also be accelerated, although details of how this is achieved are not known at this time. Reconnection in the outer region of the closed magnetic field injects the trapped particles from time to time into the interplanetary medium as impulsive events, while leakage provides a dribble of ions into the interplanetary medium, to provide the quiet time background. The trapped ions may also be seed particles for acceleration in a chromospheric flare. The flare acceleration does not preferentially accelerate ^{3}He nor ultra-heavy ions.

Key words. Sun: corona – Sun: particle emission – Sun: coronal mass ejections (CMEs)

1. Introduction

Since the discovery of solar energetic particle events with a greatly enhanced ^{3}He/^{4}He ratio over solar system abundances (Hseih & Simpson 1970) there has been considerable theoretical and experimental effort to understand the physical processes responsible for such a dramatic enhancement. The baseline solar system ^{3}He/^{4}He abundance ratio is assumed to be that measured in the quiet-time and slow solar wind (Gloeckler & Geiss 1998) of around 4×10^{-4}. It was quickly realised that events with the highest ^{3}He/^{4}He ratio were small energetic particle events. Later it was discovered that the ^{3}He-rich events were normally accompanied by impulsive mildly-relativistic electron events, which are almost invariably associated with type III radio bursts (Reames et al. 1985). There is strong observational evidence that the most common impulsive solar electron events are accelerated in the high corona (Potter et al. 1980; Lin 1985; Simnett 2006).

The association of ^{3}He events with impulsive electron events gives us an important clue as to where the primary ^{3}He acceleration is occurring, if we assume that the ^{3}He is energised along with the electrons. Cliver & Kahler (1991) suggested that the location of the preferential acceleration of the ^{3}He was also high in the corona. However, this has not gained widespread support. Reames (1999) has argued that particle acceleration in large solar energetic particle events is at a CME-driven shock, and that the acceleration of particles in impulsive events takes place in a solar flare. The information gleaned from a thorough analysis of the ^{3}He-rich events supports a rather different explanation as we shall show in this paper.

Particle acceleration to high energies, e.g. >50 MeV/nuc, does occur at times of large Hα flares and we believe that a non-thermal seed population, originating in the high corona, is an important and necessary input for energetic particle production at or near the flare site.

Observations over the energy region from ~80 keV/nuc to 15 MeV/nuc (Mason et al. 2002) have focused on the ^{3}He/^{4}He ratio as a function of energy. The ^{3}He spectrum is frequently quite different to that of protons, light nuclei and ^{4}He, although the iron spectrum often matches that of ^{3}He. This would indicate that the ^{3}He acceleration must be a unique and distinct process to that energising the other commonly-observed light nuclei. Therefore we reconsider the possibility, first proposed by Cliver & Kahler (1991), that the location of the acceleration region for ^{3}He is in the high corona and is different to that where most nuclei from solar energetic particle events are accelerated. The physical parameters in the region favour preferential acceleration of ^{3}He, possibly together with heavy ions.

By way of contrast, the association of intense energetic particle production with large solar flares leads to the conclusion that the bulk of the acceleration to the highest energies occurs near the region where the brightest optical and X-ray emission occurs, namely low in the solar atmosphere and in a magnetically-complex active region. This process does not favour ^{3}He; but neither does it exclude ^{3}He acceleration. We suggest that some of the ^{3}He which is selectively energised in the high corona may act as a seed population for further acceleration in the flare region, and the degree to which this happens leads to the huge variation in the ^{3}He/^{4}He ratio observed in the flare-associated events. Reames et al. (1988) showed that for these flare events there was no correlation between the soft X-ray temperature and intensity and the ^{3}He/^{4}He ratio. This supports the hypothesis that the helium ions contributing to the high ^{3}He/^{4}He ratio must be accelerated in a different part of the Sun to the location of the soft X-ray emission.

If a list is made of events where ^{3}He is identified, then two things emerge. The first is that the largest events are normally associated with an identified solar flare and the second is that if all events are included, the ^{3}He/^{4}He ratio is highly variable,

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probably over at least four orders of magnitude. Mason et al. (2004) selected 20 events seen by the Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on the ACE spacecraft where the ^{3}He/^{4}He ratio varied by about two orders of magnitude. A study of smaller, impulsive ^{3}He-rich events (Mason et al. 2002) covered ^{3}He/^{4}He ratios from around 5×10^{-2} to over unity. Frequently the energy spectrum of the two isotopes is different.

Another property of ^{3}He-rich events is that heavy ions such as neon and iron are enhanced relative to, say, oxygen. Ultra-heavy ions may also feature in the acceleration process. Reames (2000) first reported measurements from the WIND spacecraft of the abundance of nuclei with atomic number Z from 34−82 in solar energetic particle events. Mason (2007) has reported similar measurements from the ACE spacecraft, where he has shown that their presence at 1 AU is correlated with the ^{3}He intensity.

The most promising theoretical explanations for preferential acceleration of ^{3}He involve some kind of resonant process (Fisk 1978; Temerin & Roth 1992; Roth & Temerin 1997). Roth & Temerin (1997) propose that the ^{3}He and heavy ion acceleration are "accelerated resonantly by electromagnetic hydrogen cyclotron waves". They recognise that efficient acceleration requires both a sufficiently intense wave density and sufficient time in resonance. The limiting factor affecting the resonance time is Coulomb collisions, which are minimised the lower the ambient density. They specifically address acceleration near a flare site, where the ambient density might be typically around 10^{10}/cm^3. They did not consider acceleration in the high corona. We suggest in this paper that the location of the initial ^{3}He and heavy ion acceleration is in the very low β plasma of the high corona at radial distances of 2−4 $R_\odot$. The accelerated particles provide a seed population for further acceleration at the flare site.

2. The three new observations

The early measurements of ^{3}He-rich periods made prior to the era covered by the WIND and ACE spacecraft established that the events were often accompanied by impulsive near-relativistic electrons and were not likely to be asssociated with large flares or fast, wide coronal mass ejections. Three important new facts have emerged over the last decade.

The first is the fluence limit reported by Ho et al. (2005). The second is the realisation that ultra-heavy nuclei are emitted at times of ^{3}He enhancements, but that most ^{3}He enhancements are not accompanied by ultra heavy nuclei at the limit of sensitivity of the detectors. The third is the presence of an enhanced population of ^{3}He in the interplanetary medium during solar quiet times (Desai et al. 2006; Al-Dayeh et al. 2008) and that this enhancement is greater during solar maximum than solar minimum. We shall now discuss these topics in more detail.

2.1. The ^{4}He fluence limit

Ho et al. (2005) concluded that there is a maximum fluence of ^{3}He in any given ^{3}He-rich event. This is perhaps a surprising result which may not endure once more data become available, although a recent update (Ho et al. 2007) reinforces their original paper. Here we adopt the premise that this result is robust. The most straightforward interpretation is that the acceleration region has a typical scale size, and that approximately all the ^{3}He in the acceleration volume gets accelerated (Roth & Temerin 1997). The location is such that it must be difficult to replenish the accelerated ^{3}He with fresh ions to be accelerated, otherwise there would be no maximum fluence. The proposed theoretical ^{3}He acceleration mechanisms are slow, which therefore precludes rapid acceleration from the ambient plasma in an impulsive flare.

Let us examine what this implies. (1) The source region cannot be below the transition region, as the the chromosphere represents a semi-infinite source of material. (2) The source region cannot be the interplanetary medium with "left-over" suprathermal ions, as suggested by Mason et al. (1999) as this would not naturally lead to a maximum fluence. (3) If virtually all the ^{3}He in the coronal source region is accelerated, the energy spectrum will tend to have a peak or at least flatten towards low energy, as there will be few low energy particles, because they have all been accelerated. The high energy side is restricted by the limit of the accelerator. This is consistent with observations (Mason 2007). With these considerations in mind, the maximum fluence result of Ho et al. (2005) supports the hypothesis that the source region is a high coronal loop where the supply of ^{3}He is finite. If essentially all the ^{3}He in such a loop were to be energised, by a process we shall address briefly in Sect. 6, with a significant fraction, say ∼50%, emitted into the interplanetary medium, then a fluence limit would follow naturally. The maximum fluence would then correspond to the maximum size of large coronal loop systems. Note the ^{4}He would not be subjected to a fluence limit if most of it is accelerated along with other light nuclei at a flare site. It is controversial as to whether the nuclei might be accelerated at a CME-driven shock (Sect. 2.3), but provided that the acceleration in flares or CMEs does not preferentially accelerate ^{3}He, then this does not affect the fluence limit.

Deriving the fluence is quite difficult as it is necessary to make assumptions about particle propagation through the high corona and in the interplanetary medium. We know, howevever, from the fact that energetic particles reach a spacecraft in the ecliptic plane at 1 AU rapidly from flares many 10s of degrees away in both latitude and longitude from the nominal footpoint of the magnetic field line linking the spacecraft to the Sun that the emission from flares must be distributed over a wide solid angle. On the other hand, not all impulsive electron events seen at WIND are detected by ACE, which would not be surprising if we postulate that impulsive events are emitted from a transient opening of magnetic field lines in the high corona which injects particles onto a much narrower cone than the output from flares plus coronal mass ejections.

2.2. Interplanetary observations of ultra-heavy nuclei

Reames (2000) first reported observations in the 3.3−10 MeV/amu region of ultra-heavy nuclei at around 1 AU. He emphasised that the acceleration of ultra-heavy nuclei was more likely to occur in conjunction with small impulsive flares than with large, gradual solar energetic particles associated with coronal mass ejections. Reames showed that over half the $Z \geq 70$ ions observed during the first 5.5 years of operation of WIND were detected in conjunction with a series of small, impulsive solar events covering a three day period in September, 1998 (see his Fig. 4). Figure 1 shows the 38−53 keV electron intensity measured on ACE by EPAM (Gold et al. 1998) for this period, and there are at least nineteen impulsive injections of electrons during the three days covered by the plot. The electron intensity is plotted in four sectors (see figure caption). The onsets of the individual electron events are typically highly anisotropic, which shows that they have propagated scatter free from the Sun, and the fast rise and decay shows that they were also released impulsively.

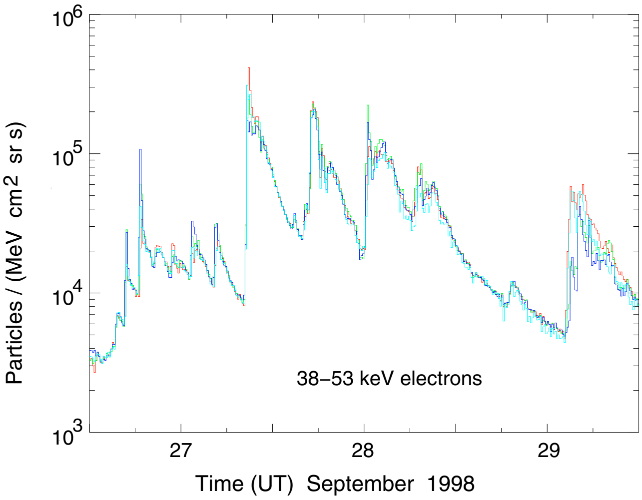

Fig. 1. The ~38–53 keV electron intensity measured by EPAM from 12 UT on 26 September to 12 UT on 29 September, 1998. The electron intensity is monitored over four 90° sectors of the spacecraft spin, shown as red, blue, green and cyan, and is plotted as 5 min averages.

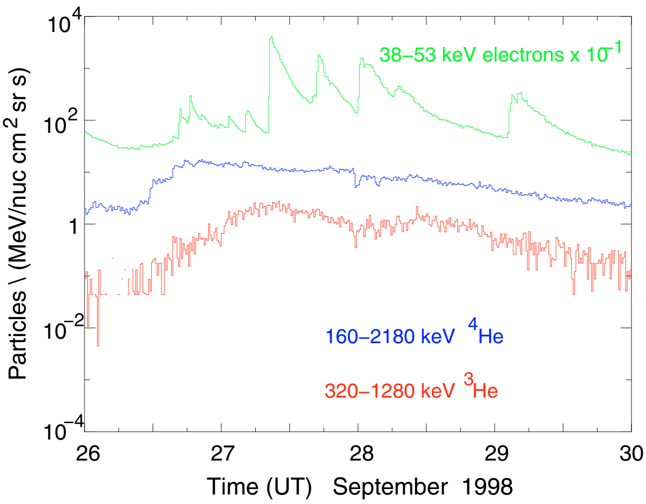

Fig. 2. The ^{3}He and ^{4}He intensity-time history for the period 26–29 September, 1998. The data are plotted as 15 min averages. Also plotted is the 38–53 keV electron energy band.

One conclusion from this is that the physical process or processes, plus the condition of the solar corona, that can produce such a series of impulsive near-relativistic electron events also provides favourable parameters for the acceleration of ultra-heavy nuclei and ^{3}He. Figure 2 shows the intensity-time history for ~0.5 MeV/nuc ^{3}He and ^{4}He nuclei measured at ACE from 26–29 September, 1998 and it is clear that this period is ^{3}He-rich. The ^{3}He intensity is not well correlated with ^{4}He.

Mason et al. (2004) and Mason (2007) have measured ultra-heavy nuclei with ULEIS, and found that the ultra-heavy nuclei occur almost exclusively during periods when ^{3}He is prominent (see Mason 2007, his Fig. 6). The electron data show that impulsive electron events were prominent during the time period selected by Mason, but they were not as dramatic as those shown in Fig. 2.

2.3. *The quiet time ^{3}He intensity in the interplanetary medium*

Mason et al. (1999) first noticed that enhanced intensities of ^{3}He were present in the interplanetary medium most of the time. They suggested that the enhanced ^{3}He intensity at quiet times arose through the acceleration of remnant flare particles by interplanetary shocks. This seems unlikely to us, as the energetic particles associated with the strongest shocks do not typically have unusually high ^{3}He/^{4}He ratios. Nor do they accelerate ions and electrons to any large degree. Ho et al. (2008), using ACE data, showed that most fast forward shocks do not accelerate energetic ions to MeV energies nor electrons above 50 keV.

Torsti et al. (2003a) noted that in the energy region 15–120 MeV/nuc ^{3}He normally was enhanced over the solar wind values. They concluded that a ^{3}He/^{4}He-ratio of ~0.015 should be regarded as the normal abundance ratio, rather than the value derived from the solar wind.

Wiedenbeck et al. (2000) suggested that the enhanced intensities were produced by a large number of small, impulsive events which were too small to be detected by normal instrumentation. Our conclusions support this hypothesis. Desai et al. (2006) (their Fig. 5) studied the ^{3}He/^{4}He ratio at quiet times from the launch of ACE in 1997 through January 2006. During solar maximum they found the ^{3}He/^{4}He ratio at 0.35–1 MeV/nuc to be typically 1.5–5%, but it dropped by an order of magnitude after the end of 2004. The low level has continued during solar minimum (Al-Dayeh et al. 2008). They concluded that there were two different sources, namely solar maximum and solar minimum, with the former dominated by multiple discrete events and the latter by ions accelerated out of the solar wind or accelerated in co-rotating interacting regions.

We agree that there should be different sources, by invoking the high coronal source, which accelerates the ^{3}He from the ambient plasma, plus a source in the flare region. The possibility of a third source, acceleration at the CME-driven shock, would simply act on the population present from the first two sources, and would not be the major player. As we have pointed out, Ho et al. (2008) show that fast forward interplanetary shocks do not in general accelerate ions and electrons to high energies.

3. Characteristics of the electron events at the time of ^{3}He-rich events

It is important to find something uniquely associated with ^{3}He-rich events. The closest we can get is to study impulsive electron events. Then if we can identify a source for these electrons we have good grounds for having the same source for the ^{3}He.

Over the last decade there have been observations of ^{3}He-rich events in the MeV/nuc energy region from the ACE/ULEIS instrument (Ho et al. 2003; Wang et al. 2005, 2006). These papers addressed various aspects of ^{3}He-rich events and together they reported on 37 events between 1997 and 2003. We have studied the characteristics of the electrons associated with these events where present above the pre-existing background. For convenience we have used the electron data from ACE/EPAM so that both the electrons and ^{3}He are measured at the same spacecraft.

3.1. *Timing*

In general the ion release time from the Sun may be determined to an accuracy of ~1 h. The release time for the electrons is

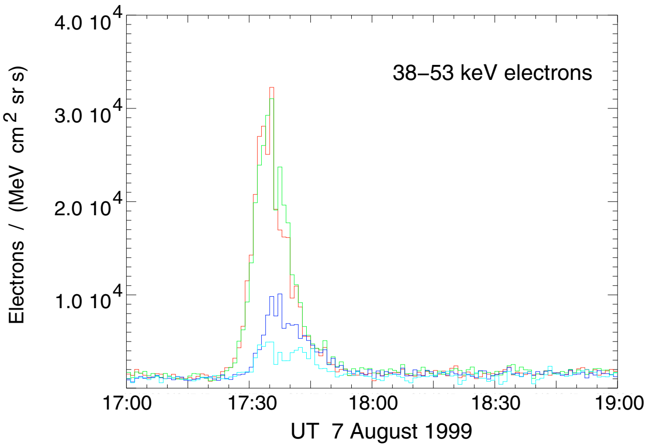

Fig. 3. The intensity of 38–53 keV electrons at ACE between 17:00 and 19:00 UT on 7 August, 1999. The four sectors of the spacecraft spin are shown separately, averaged over 1 min.

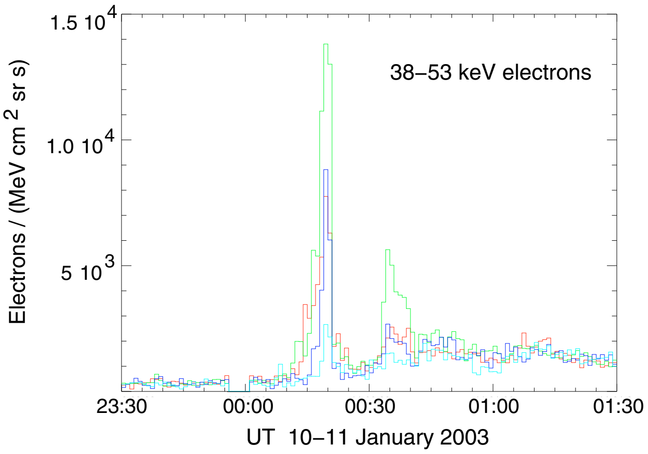

Fig. 4. The intensity of 38–53 keV electrons at ACE between 23:30 and 01:30 UT on 10/11 January 2003. The four sectors of the spacecraft spin are shown separately, averaged over 1 min.

better determined, typically to within 15 min. This then narrows the time window within which we might search for related Hα, soft X-ray or UV events at the Sun. Wang et al. (2006) reported on 25 events, of which 8 had no associated electrons. The events studied by Ho et al. (2003) and Wang et al. (2005) were selected because there were associated electrons. We have examined the 29 residual electron events, concentrating on the intensity-time history, the anisotropy, the peak intensity in the 38–53 keV energy band, and the energy spectrum. Most of these events were not associated with flare activity if we restrict the time window based on the electron onsets.

3.2. Intensity-time profile

In most of the 29 events the electrons arrived at the spacecraft as a collimated beam. In the chosen examples we show the intensity in four sectors of the spacecraft spin separately. Figure 3 shows a period on 7 August, 1999 where the electron event lasts about 15 min at 38–53 keV. We refer to this type of profile as a simple *pulse*. This event has an almost symmetrical rise and fall, with negligible backscattering. Backscattering manifests itself if the intensity does not decay to the pre-event level, generally with little anisotropy.

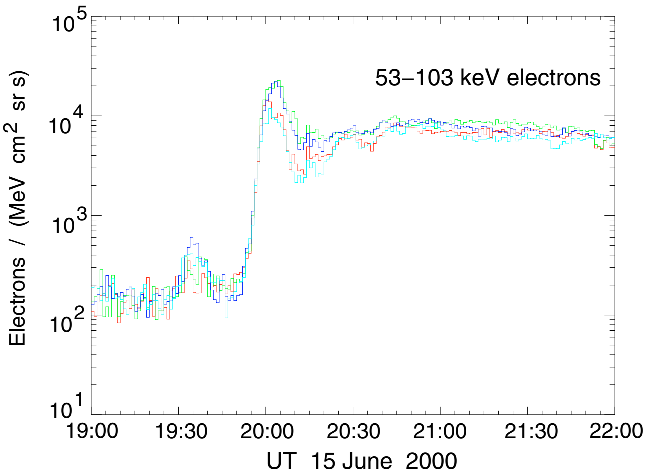

Fig. 5. The intensity of 53–103 keV electrons at ACE between 19:00–22:00 UT on 15 June, 2000. The four sectors of the spacecraft spin are shown separately, averaged over 1 min.

The electron events often occur as double pulses and an example of this, on 11 January, 2003, is shown in Fig. 4. Each pulse lasts around 10 min, but there is now evidence of backscattering as the intensity following the second pulse does not decay to the pre-event background level but continues as an almost isotropic decay for over an hour. This behaviour is interpreted as backscattering of the electrons from somewhere beyond 1 AU.

Some events exhibit two pulses of electrons and then have a long-lived increase superimposed later. An example of this is shown in Fig. 5 for an event on 15 June, 2000. The 53–103 keV energy range is illustrated as the two pulses are more distinct in this energy range. Events such as this must involve significant scattering as the later phase of the event is almost isotropic. A simple explanation is that in addition to the two electron pulses, which we suggest are produced by the acceleration mechanism that also accelerates ^{3}He, there is a much larger event, emitted over an extensive area which populates a significant volume, encompassing the spacecraft, with electrons. Such electrons are quasi trapped, resulting in the long and near-isotropic decay.

In the events illustrated so far the electron pulses have been distinct in the 38–53 keV energy range. This is not always the case. The event on 24 September 2002 is illustrated in Fig. 6 and it has a complex intensity-time profile at 38–53 keV (upper panel). However, in the 103–175 keV range (lower panel) there are clearly two distinct electron pulses, rather similar to the 15 June event shown in Fig. 5. There is residual low level emission for over an hour after the decay of the second pulse, similar to the 11 January 2003 event (Fig. 4). Without the observations at higher energy it would be difficult to interpret the 38–53 keV data. Note the velocity dispersion in the data.

Somewhat arbitrarily we define an electron pulse as an event lasting less than 40 min, full width at 1/4 maximum. With this definition 21 of the 29 events were pulses. Two more had slightly bigger widths, of 50 and 60 min respectively. The large flare-associated event on 9 September, 1998 rose to a maximum which was a factor of 30 higher than the second pulse at 38–53 keV. This event is shown in Fig. 7. It clearly starts off like a double pulse event, but it continues with even more pulses, of ever increasing intensity, until it becomes a major electron event. At energies above 100 keV the pulses seen at 38–53 keV are not visible and at those energies the event appears as a “typical” flare electron event, with a fast rise to maximum and a

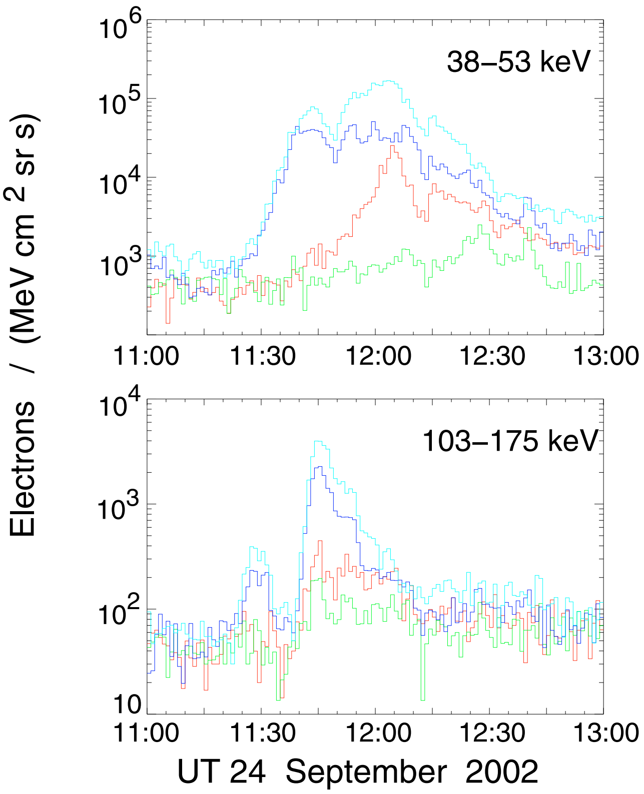

Fig. 6. The intensity of 38–53 keV (*upper panel*) and 103–175 keV (*lower panel*) electrons at ACE between 17:00–19:00 UT on 24 September, 2002. The four sectors of the spacecraft spin are shown separately, averaged over 1 min.

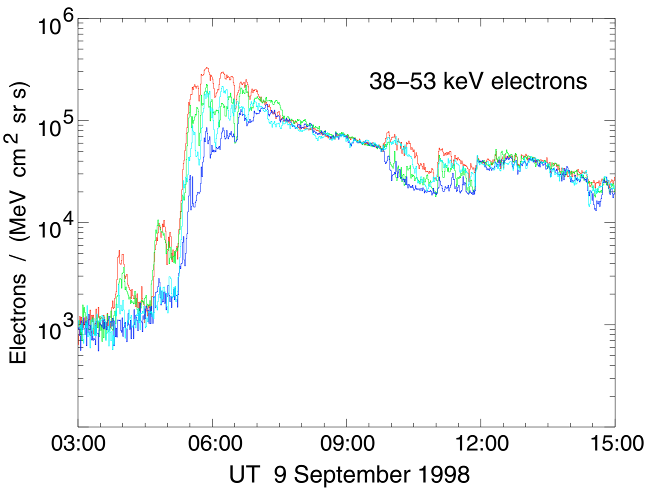

Fig. 7. The intensity of 38–53 keV electrons at ACE between 03:00–15:00 UT on 9 September, 1998. The four sectors of the spacecraft spin are shown separately, averaged over 1 min.

monotonic, exponential decay. There was no Hα flare reported in Solar Geophysical Data (US Dept. of Commerce, Boulder, CO), but there was a short soft X-ray event at the GOES M2.8 level at 04:52 UT, which is around the peak of the second electron pulse. This could be the signature of the trapped coronal electrons impacting the chromosphere.

In summary, if we include the 9 September 1998 event as an example of electron pulses, then 24 out of 29 ^{3}He-rich events are associated with one, two or possibly more pulses of duration typically 20–30 min.

3.3. Magnetic connection to the Sun: anisotropy

In the previous section we have plotted the electron intensity-time profiles for all quadrants of the spacecraft spin. Typically the difference between the various sectors is a good indicator of the electron anisotropy. However, if the magnetic field vector is close to the spacecraft spin axis, then to measure the anisotropy we need to examine the pitch angle distribution in detail. Figure 8 shows the pitch angle distribution for representative electron pulses. The energy channels plotted are from ACE/EPAM DE2 (38–53 keV; blue letters A–D) and LEFS60 E'2 (64–112 keV; red numbers 1–8). The peak intensity, S, relevant to the plot is given in each panel in units of electrons/(MeV cm^2 sr s).

The left panel shows the peak of the 15 June 2000 event (see also Fig. 5). The pitch angle distribution is relatively broad showing that in addition to the beam propagating along the magnetic field there is a significant component travelling back towards the Sun. The centre panel shows the 19 August 2002 event, which has a more collimated beam, with the backscattered component of ~10%. The right panel shows the 24 September 2002 event, which is an example of the most highly collimated events seen at ACE. For clarity the lines linking the various sectors have been omitted. Note that for all three events the interplanetary magnetic field is conventionally towards the Sun.

The electron pulses typically have strong anisotropies, indicating that the spacecraft is (a) magnetically connected to the electron source and (b) that there has been little scattering on the way from the Sun.

3.4. Intensity

The peak intensity of the 38–53 keV electrons has been studied and a histogram of the 29 events is shown in Fig. 9. As discussed above, 23 events (for this purpose we omit the event on 9 September 1998) have intensity-time profiles which qualify the event as *pulsed*. There is a dearth of small events with peak intensity below 3×10^3 electrons/(MeV cm^2 sr s). However, the event selection is controlled by the ^{3}He intensity being above the instrumental sensitivity. The most intense pulse was on 1 May, 2000 with a peak intensity of ~10^6 electrons/(MeV cm^2 sr s). This event was not typical as the pitch angle distribution was close to isotropic throughout and the event had a long (several hours) decay starting at a few % of the peak intensity. We interpret this as an intense electron pulse from a source not magnetically-well-connected to ACE. There was a GOES soft X-ray burst at the M1.1 level but no reported Hα flare (Solar Geophysical Data, *ibid*), which would be consistent with a source beyond the solar west limb.

3.5. Energy spectrum

The energy spectrum for the electron pulses is soft in comparison to a typical solar flare spectrum (Simnett 2006). Out of the 23 pulse events where the detected electron energy was high enough for the spectrum to be measured by ACE/EPAM, the median value for the differential spectral index was −3.9. For four events the spectral index was steeper than −5, which suggests a cut off to the electron energy of a few hundred keV. There is a tendency for the events with the highest intensity to have a harder spectrum.

Where the electron pulse is followed by a major flare event the spectral index from the flare electrons is typically much

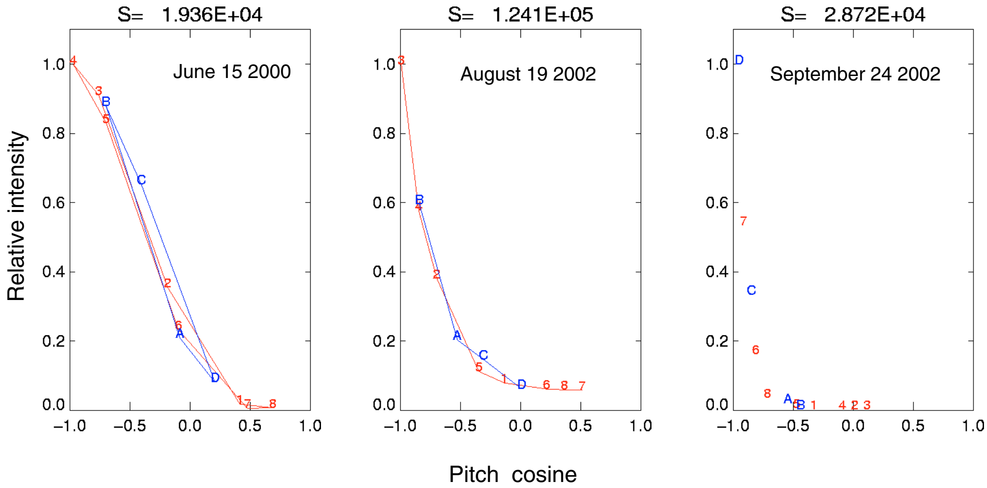

Fig. 8. The electron pitch angle distribution from the ACE/EPAM DE2 and E'2 electron channels (∼50–100 keV). *Left panel*: 15 June 2000 event. *Centre panel*: 19 August 2002 event. *Right panel*: 24 September 2002 event. See text.

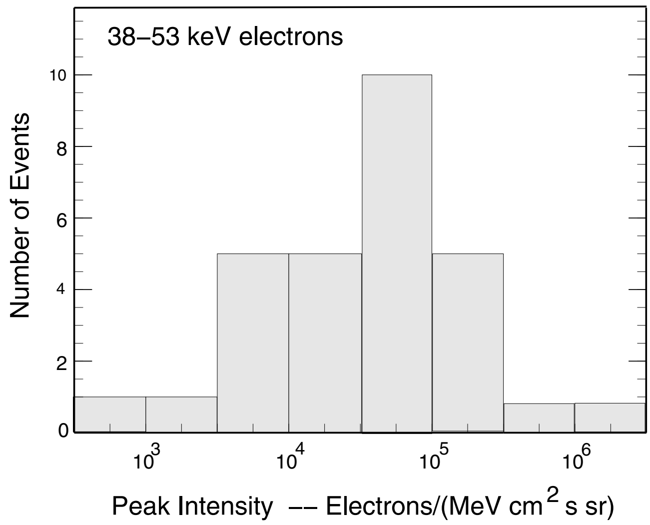

Fig. 9. The peak intensity of 38–53 keV electrons in the ^{3}He-rich events.

harder that that for the pulse. For example, for the event on 15 June, 2000, the spectrum during the decay has a spectral index of −2.9, while at the peak of the pulse it is 3.6. This behaviour is consistent with two electron sources.

3.6. Summary

It is clear from this study that ^{3}He-rich events are typically associated with one or two pulsed beams of near-relativistic electrons. The double pulses where observed are separated by ∼1 h. Most of the observed events appear to be well-connected to the solar source, based on the pitch angle distributions of the electrons. Solar particle events associated with major Hα flares are not typically ^{3}He-rich, which would confirm that the ^{3}He-rich events originate in a process not closely related to Hα flares.

The model we envisage to explain these results is one which involves high coronal loops extending to several $R_\odot$. Such loops at these altitudes are probably not very stable so that magnetic reconnection events are quite likely. The energy released accelerates electrons and ^{3}He, plus other ions which happen to match the resonance conditions briefly mentioned in Sect. 6. The timescale involved is of the order of the duration of the electron pulse, or less. There may be more than one reconnection event produced as the coronal magnetic field adjusts to a new equilibrium state. Typically an observing spacecraft such as ACE might be magnetically connected to only one or two high altitude sources, but occasionally there may be more. For example, events such as that shown in Fig. 7 have several pulses together with a very substantial, slowly-varying background. The coronal magnetic field, when mapped back to the photosphere, may involve an active region about to flare. In this case the fraction of the accelerated ions and electrons which remain in the corona could be available as a seed population for the "flare". However, for most of the events this does not happen, in that there is no associated flare.

4. ^{3}He emission from the quiet Sun

A further piece of evidence that the ^{3}He acceleration out of the thermal plasma is from neither flares or CME-driven shocks comes from observations of long-lived ^{3}He events such as shown by Mason (2007) (his Fig. 7). This event occurred in a solar wind dwell (Nolte & Roelof 1973) where the solar wind at the observing spacecraft falls monotonically over several days. This indicates that the observing spacecraft is magnetically connected to a coronal hole, which therefore is not close to an active region, nor is it likely to be the source of large CMEs. Furthermore, if the dwell continues for several days, this suggests that (magnetically) the interplanetary medium between the spacecraft and the Sun is quiet.

There are a number of such dwells seen in the ACE data at times of ^{3}He enhancements. Figure 10 shows the solar wind speed and the ^{3}He intensity for four events (see figure caption). In each example there is a ^{3}He event near the end of the solar wind dwell. The first event in January 2000 also has a ^{3}He event near the beginning of the monotonic fall in the solar wind speed, which was plausibly associated with a 1N Hα flare at N24W35 (Solar Geophysical Data, *ibid*). There was no obvious flare candidate for the second ^{3}He increase. There were no reported Hα flares on Feb. 2, isolated Hα sub-flares on December 31, 2002; and similarly on October 11–12, 2005. Thus the ^{3}He events shown in Fig. 10 do not appear associated with solar flares. This was also the conclusion of Mason (2007) for the October 2005 event.

5. The ^{3}He and ^{4}He intensities at 1 AU from flares

At energies from around 0.1–1 MeV/nuc the intensity of ^{3}He and ^{4}He has been monitored by ULEIS since the launch of ACE in August 1997 to the present time. During this period many large, discrete events have been detected and for about half the

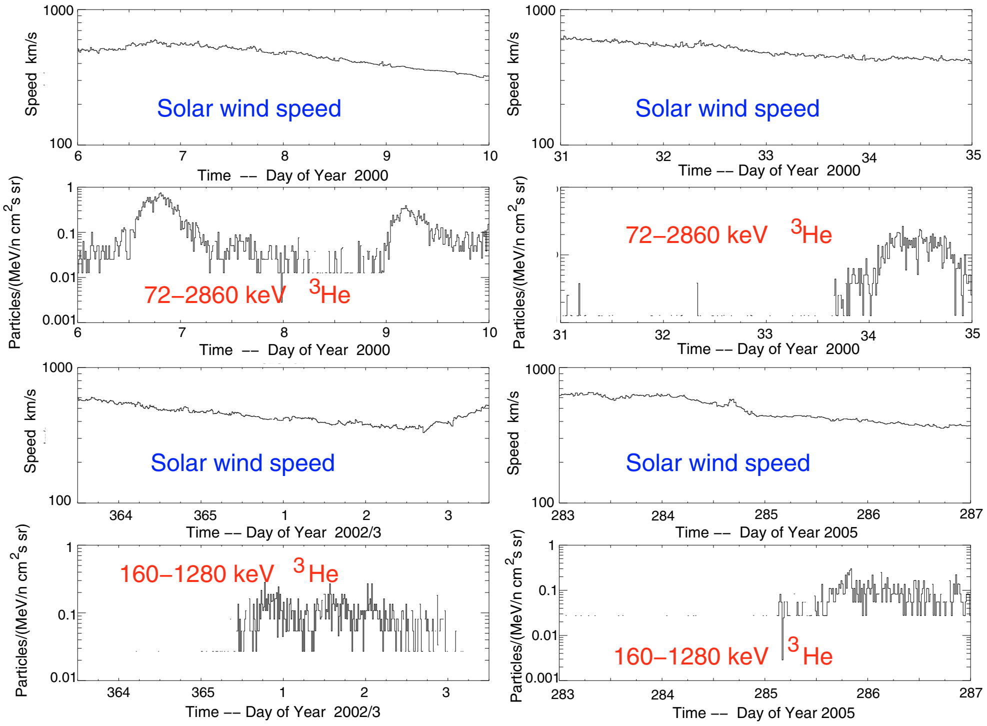

Fig. 10. The solar wind speed (*upper panels*) and the ^{3}He intensity at the ACE spacecraft for four events: 6–10 January 2000; 31 January–4 February, 2000; 29.5 December 2002–3.5 January 2003; 10–14 October 2005.

^{3}He intensity has tracked the ^{4}He intensity at a level consistent with about five times the solar wind abundance (Mason et al. 1999). Near-relativistic electrons are monitored by ACE/EPAM and it is of interest to compare the ^{3}He events with the electron intensity.

Figure 11 shows some examples of typical solar energetic particle events, where the ^{3}He and ^{4}He intensities have similar time profiles and are not considered ^{3}He-rich. In all these events the ^{3}He intensity is around the 1% level compared with ^{4}He and this is the sensitivity level of ULEIS. Also plotted in Fig. 11 is the 53–175 keV electron intensity, and it is clear that the electron events are long-lived, and smoothly decaying. The time duration for the events is two to three days.

Figure 12 shows some ostensibly similar events, but in fact the intensity-time profiles are subtly different. In panel (a) there is an initial burst which is ^{3}He-rich, following which the ^{3}He and ^{4}He intensities have similar time profiles for about a day, when the ^{4}He intensity rises without a corresponding rise in ^{3}He. In some of the other events, notably (b), (c), (d) and (e) the ^{4}He intensity continues to rise after the ^{3}He intensity has reached a maximum. Event (f) has a low level of ^{3}He, but does not increase as the ^{4}He intensity rises. All the events are associated with an Hα flare and in most of the events shown the electron intensity is long-lived.

There are other events where the ^{3}He and ^{4}He intensities are quite different, and some of these are shown in Fig. 13. In several events ^{3}He dominates ^{4}He. In only one event, *d*, is the accompanying electron intensity long-lived. The associated electron intensity for the other events is typically short-lived, and events e and f exhibit multiple bursts. It is plausible that in event c the associated electron burst was not detected by ACE, and the visible burst is associated with slight increase in ^{3}He around 23:00 UT on 21 March (DOY 80).

These events are all small, ^{3}He-rich and generally are not associated with Hα flares above the level of sub-flares. However, there was a class 1B flare from S19W23 at 14:28 UT on 20 October, 2002 for the event in panel (e). Unlike the events shown in Figs. 11 and 12, five of the events shown in Fig. 13 are at times when impulsive electron bursts are detected.

5.1. The highest energy ^{3}He observed

Torsti et al. (2002) have reported a possible flare-associated ^{3}He-rich event in the energy range 15–30 MeV/nucleon from SOHO data on 29–30 October, 2000. The ^{3}He/^{4}He ratio reached a maximum of 1.4. The event was unique in this respect. At energies around 1 MeV/nuc ULEIS measured a ^{3}He/^{4}He ratio below 0.1, so that this event was not particularly worthy of note at this energy. We would interpret this behaviour as a flare event where acceleration stopped just as all the ^{3}He seed population had been re-accelerated. This would naturally be rather rare. In events where the flare acceleration continues, the ^{3}He/^{4}He ratio changes from ~1 towards the value relating to the chromospheric abundance ratio (presumably around a few times 10^{-4}).

Torsti et al. (2003a) have studied ^{3}He at energies above 15 MeV/nucleon. They find that ^{3}He is present in all strong ^{4}He events such that the ^{3}He/^{4}He ratio is well above solar wind values. They note that if the high energy ^{3}He is produced by shock acceleration in the large gradual events then a ^{3}He/^{4}He ratio more nearly that of the quiet solar wind should be found. This is not the case.

Torsti et al. (2003b) have measured the ^{3}He/^{4}He ratio in four events which might have originated in a strong, impulsive flare. The flare association is not very strong, as the possible flares are both well separated in time and location. They allow a window of 13–20 h for the flare time versus the ^{3}He onset at 1 AU and 40°–100° for the location separated from the nominal interplanetary field connection. However, in the four events they note that while the ^{3}He/^{4}He ratio is typical of an impulsive energetic particle event, the time profiles of these events were more typical of a gradual energetic particle event. They conclude that the rare high energy ^{3}He-rich events "have a very different pre-acceleration history" to the typical ^{3}He-rich event observed at 0.5–2 MeV/nuc. Torsti et al. (2003b) suggest that the impulsive

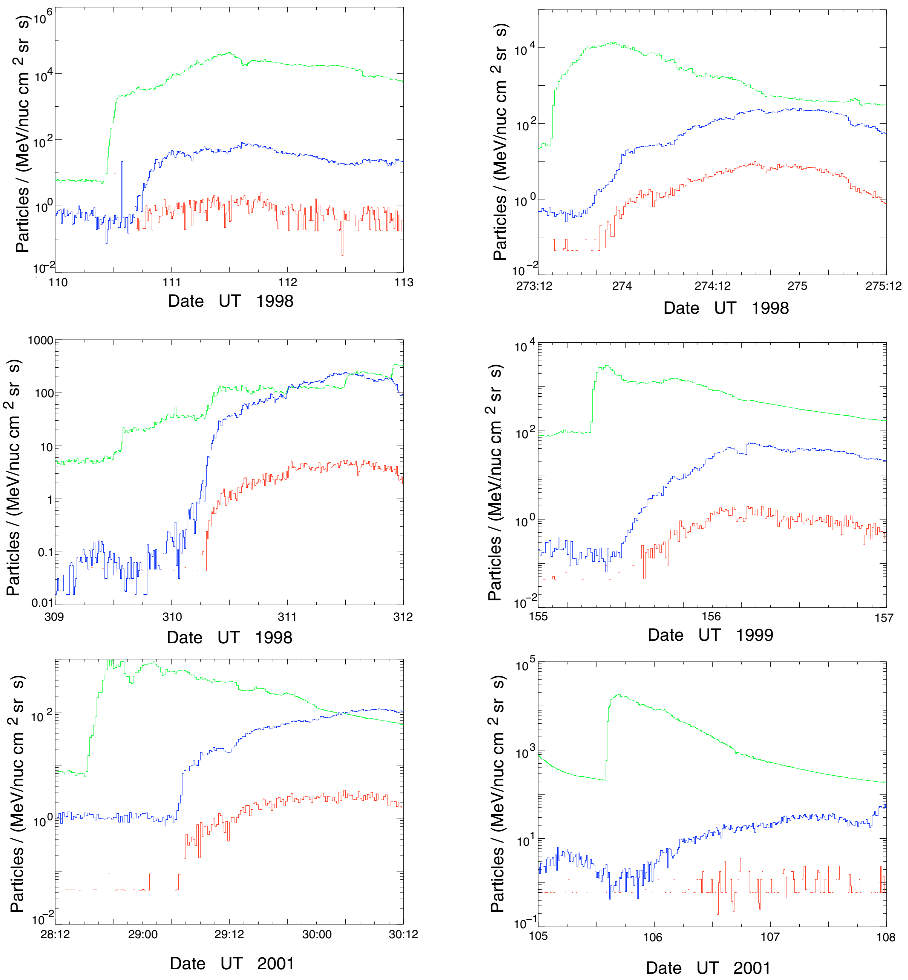

Fig. 11. The 53–175 keV electron intensity (green) and the ^{3}He (red) and ^{4}He (blue) intensities for some typical solar energetic particle events which are well-identified with solar flares. The intensity of the electrons is plotted at one tenth of the true intensity.

flare observed 13–20 h earlier provided the seed population of ^{3}He which then is further accelerated in a CME-driven shock. We believe this is unlikely, as discussed below. Their explanation is rather inconsistent, as they advocate ^{3}He acceleration to energies ∼1 MeV in impulsive solar flares which get further accelerated in an interplanetary shock. If this were true, then we would expect the high energy ^{3}He-rich events to be quite common.

Torsti et al. (2003a) looked for days when the ^{4}He intensity was above 0.5 ions/(m^2 s sr MeV/nuc) and measured the ^{3}He intensity for those days. At 15–30 MeV/nuc they found that the ^{3}He/^{4}He ratio had a peak value of 0.015 (see their Fig. 2). There were 167 days out of a 22-month period when the ^{3}He intensity exceeded their selection criterion. They stress that this is not what they would have expected if the ^{3}He was accelerated at travelling interplanetary shocks driven by CMEs (Reames 1995). The most frequent ^{3}He/^{4}He ratio was ∼0.01, well above the ^{3}He/^{4}He-ratio found in the solar wind.

5.2. Provenance of the energetic particles observed in association with interplanetary shocks

The ion energy spectrum measured in situ in the vicinity of strong interplanetary shocks may show a local maximum in the 0.2–1 MeV region. (Simnett 2003; Simnett et al. 2005). This suggests that such shocks do not accelerate ions to more than a few hundred keV/nuc, and that on the occasions that higher energy particles are observed, then these are probably from acceleration the Sun, trapped within the outward-propagating CME.

Bastian et al. (2001) have imaged an expanding CME at radio frequencies (164 MHz) and have concluded that the radio emission is synchrotron radiation from 0.5–5 MeV electrons trapped in some of the expanding loops of a CME. The idea that CMEs contain trapped particles is controversial (see Reames 1999, and references therein) and it is beyond the scope of this paper to discuss it further.

Ho et al. (2008) have studied the particle acceleration associated with transient shocks seen at ACE from February 1998 through October, 2003. They identified 191 fast forward shocks which were driven or related to CMEs, out of a total of 298 shocks. 64% were associated with ion increases at 47–68 keV, 32% with increases in the 1.9–4.8 MeV region, and 20% with increases in 38–53 keV electrons. From analysis of the energy spectra close to the shock, they found that the majority of the events had a spectrum which did not agree with theoretical predictions of shock acceleration. This casts doubt on the effectiveness of such shocks to accelerate energetic particles. This is supported by the analysis presented by Torsti et al. (2003a). In the minority of cases where energetic particles are present, we suggest that these are predominantly trapped "flare" accelerated particles (Simnett 2005).

6. Theoretical models for ^{3}He acceleration

There have been many papers over the last 30 years which address the theory behind the preferential acceleration of ^{3}He. The reader is referred to Petrosian et al. (2009), Temerin & Roth (1996) and Miller & Vinas (1993) for a comprehensive discussion. The consensus is that ^{3}He acceleration to MeV/nuc

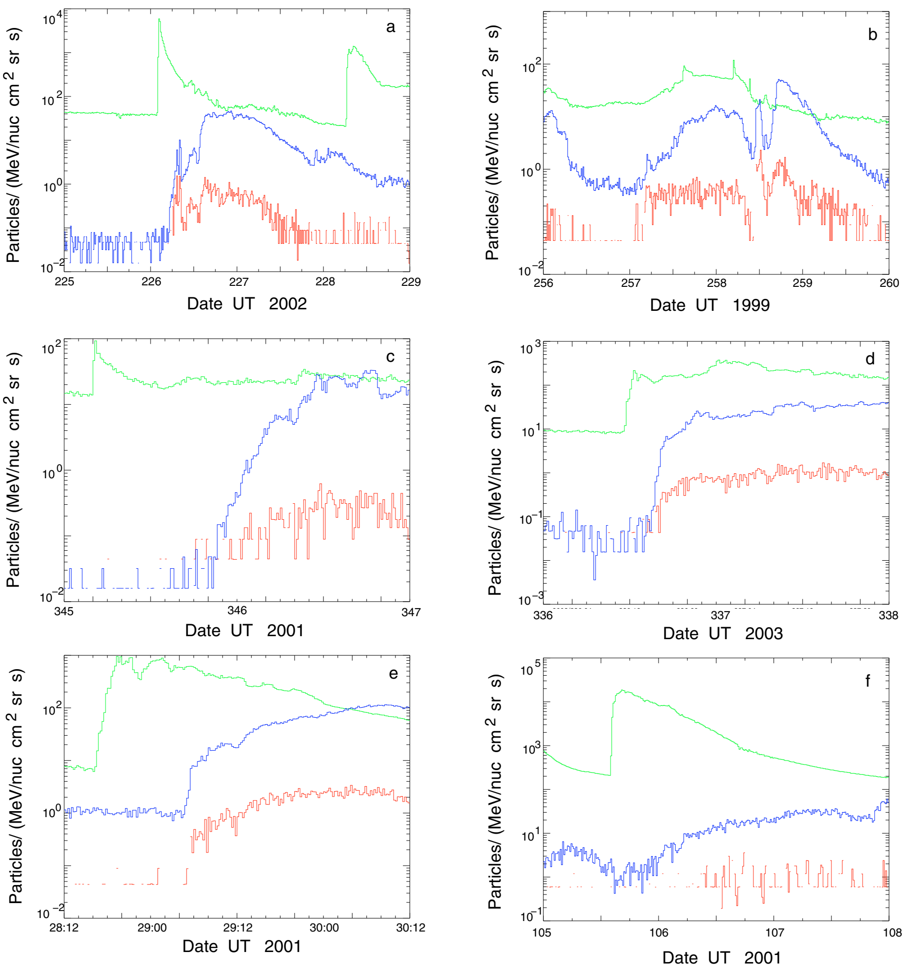

Fig. 12. The 53–175 keV electron intensity (green) and the ^{3}He (red) and ^{4}He (blue) intensities for some typical solar energetic particle events which are well-identified with solar flares, but where the ^{3}He and ^{4}He intensities are different. The intensity of the electrons is plotted at one tenth of the true intensity.

energies relies on resonant wave-particle interactions through which ^{3}He, because of its unique charge/mass ratio, is favoured.

One of the early models (Fisk 1978) showed that under certain specific conditions ^{3}He may be preferentially accelerated via wave-particle interactions. He invoked a two-stage process whereby the ^{3}He ions are first heated and then accelerated via a resonance with electrostatic ion cyclotron waves generated by ^{4}He ions. Fisk indicated that for the resonance mechanism to be effective $n_{\mathrm{He}}/n_{\mathrm{H}}$ must be >0.2 and $T_{\mathrm{e}}/T_{\mathrm{i}}$ must be $\gtrsim 5$. Here n_{He} and n_{H} are the number densities of ^{4}He and protons respectively and T_{e}, T_{i} are the electron and ion temperatures, respectively. It is possible that the high corona could match most of these conditions.

Temerin & Roth (1992) present a model whereby ^{3}He and heavy ions are accelerated in a single stage by obliquely propagating electromagnetic proton cyclotron waves. ^{3}He is accelerated when the local gyrofrequency matches the wave frequency, while heavier ions are accelerated when their gyrofrequency is half the wave frequency. Central to this theory is the fact that ^{3}He has a unique charge/mass ratio. Roth & Temerin (1997) show that at low energies the first harmonic resonance is more efficient so that heavy ions, which resonate with the second harmonic of the electromagnetic proton gyrofrequency, are not accelerated efficiently.

Temerin & Roth (1996) point out that the generation of electromagnetic proton cyclotron waves may present a problem as standard linear plasma theory suggests that such waves may not reach a sufficiently high amplitude to be effective in the acceleration process. However, they cite auroral observations of such waves associated with non-thermal electrons which produce the aurora. Therefore they argue that as such waves exist in the magnetosphere, they are likely to be present in the solar corona. Roth & Temerin (1997) note that the magnetic fields related to the auroral phenomena are ~0.1 G, whereas the magnetic field strength in the corona may be as high as ~100 G. The ion energy gain scales with magnetic field strength, so that as auroral ions have energies in the keV/nuc region, in the corona the energies should be in the MeV/nuc region.

Temerin & Roth (1992, 1996) note that auroral observations indicate that the wave energy is 0.1–10% of the streaming electron energy. Therefore in situations where we are sure that non-thermal electrons are present, as in the ^{3}He-rich events, there are likely to be high amplitude electromagnetic ion cyclotron waves which selectively accelerate ^{3}He, and in some cases heavy ions, to MeV/nuc energies.

Heavy ions do not always accompany ^{3}He-rich events in observable quantities. Temerin & Roth (1996) argue that the lack of acceleration of heavy ions in some ^{3}He-rich events is due to energy considerations plus the low efficiency of the second harmonic process at low energies.

Liu et al. (2006) show that there is a steep variation of the ^{3}He/^{4}He fluence ratio with both the level of plasma turbulence and the rate of acceleration. There are always energy losses, and clearly the success of the wave-particle interaction relies on the energy gain exceeding the energy loss. Petrosian et al. (2009) point out that at low energy, say below 1 MeV/nuc, the acceleration time for ^{4}He is one to two orders of magnitude below that

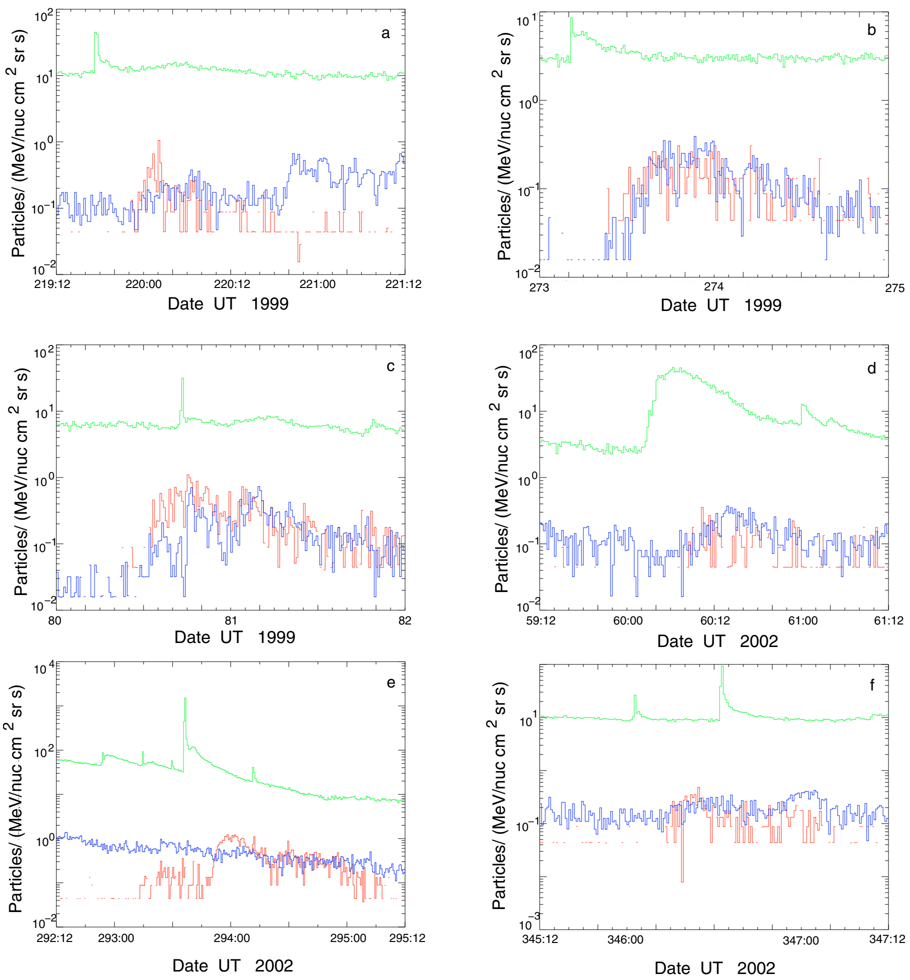

Fig. 13. The 53–175 keV electron intensity (green) and the ^{3}He (red) and ^{4}He (blue) intensities for some typical ^{3}He-rich events. The intensity of the electrons is plotted at one tenth of the true intensity.

for ^{3}He. They also show that ^{3}He, with its unique charge/mass ratio, can resonate with plasma modes not available to ^{4}He.

In summary, the theory developed over the last 30 years strongly supports the view that wave-particle interactions in turbulent plasmas, such as are likely to exist in the active corona, are central to the preferential acceleration of ^{3}He.

7. The case for acceleration of ^{3}He in the high corona

Based on the observations and interpretations presented above, we now focus on the case for the initial ^{3}He acceleration in the high corona. The structure of the coronal magnetic field is important. The impulsive electron events are consistent with the hypothesis that the acceleration site is high in the corona, say around 2 solar radii or higher. Distances we cite are all Sun-centred. The energy source is magnetic reconnection, and this may be present at considerably higher altitudes than 2 $R_\odot$ (Simnett 2004). The acceleration process (see Sect. 5.3) preferentially accelerates ^{3}He, electrons and possibly ultra-heavy nuclei. The upper energy is normally around 1 MeV/nuc for ions and around 100 keV for electrons.

Some fraction of the output of the accelerator is injected into the interplanetary medium, while the remainder is trapped in closed coronal magnetic fields. If the coronal magnetic field is connected to an active region about to flare, then the output of the *coronal accelerator* is a seed population for acceleration at the flare site (Fisk 1978). We refer to this as the *flare accelerator*. It does not selectively accelerate any particular species, and the upper limit to the energy produced is in the 10s of GeV/nuc for ions and 100 MeV for electrons.

It is significant that Torsti et al. (2003b) used as their selection criterion the the detection of a ^{4}He event above 0.5 ions/(m^2 s sr MeV/nuc). This then automatically excludes small ^{3}He-rich events. However, their Fig. 2 shows that for these small events the ^{3}He/^{4}He ratio is often much higher than the 0.015 value found using the ^{4}He intensity as the selection criterion.

Torsti et al. (2003b) identified four exceptional high energy ^{3}He-rich events where the onset at 1 AU was observed “about 2/3 (of a) day” after the associated flare/CME. This was from a 22-month sample of data from the SOHO spacecraft in 1999/2000, during which time there were many energetic particle events. Thus the ^{3}He acceleration is not an essential feature of solar energetic particle events.

7.1. Location of the source of energetic ^{3}He

There have been attempts to try to identify solar phenomena which may be present around the release time at the Sun of ^{3}He-rich events (Pick et al. 2006; Kahler et al. 2001). Optical or EUV/X-ray observations are only possible near the Sun, say to about 1.1 $R_\odot$, while imaging radio data used by Pick et al. were at decimetric wavelengths which typically image below 2 $R_\odot$. Therefore any correlations from such studies are highly selective as they demand detectable activity in the low corona.

We are proposing that the source of the energetic ^{3}He is in the very high corona around the location of the bi-directional transient events reported by Simnett (2004) using LASCO observations. These events are interpreted as deriving their energy from reconnecting closed magnetic field structures which exist to distances of around 4−5 solar radii in the low latitude streamer belt. The events discussed by Simnett (2004) originated predominantly above 3.4 $R_\odot$ and he suggested that the reconnection proceeded as originally suggested by Petschek (1964). which produced oppositely directed shocks. The particle acceleration process could now be basically electron acceleration, which excites electromagnetic ion cyclotron waves to resonate with any ^{3}He present (Temerin & Roth 1992). However, other acceleration mechanisms may be possible.

The magnetic reconnection which drives the acceleration process is driven by photospheric motions, as all magnetic field lines in the corona must at some point come through the photosphere (plasmoids excepted). Thus it is to be expected that some fraction of the high coronal events will be associated with activity in the low corona. Furthermore, the downward-directed accelerated particles may provide a seed population for input to a chromspheric flare (Fisk 1978).

Pick et al. (2006) point out that the association of coronal mass ejections with impulsive ^{3}He events is quite unusual. We wish to emphasise this further, to the extent that energy releases that accelerate the impulsive electrons and ^{3}He are a consequence of a re-adjustment of the coronal magnetic fields, which normally do not produce a detectable transient in the low corona. However, some fraction of these "readjustments" are not simply confined to the high corona, and occasionally involve more transient effects lower in the atmosphere. It is these that are the subject of the associations and correlations reported by Pick et al.

7.2. Timescale of the acceleration

The majority of the theoretical effort into understanding solar energetic particle acceleration has supposed either that the acceleration occurs rapidly around the timescale of the hard X-ray emission from a flare, or in conjunction with the passage of a fast CME through the corona. It has recently been proposed that in terms of the kinetic energy content, the majority of the energetic particle acceleration around the time of a major flare takes place gradually, but in bursts, over a period of many hours before the flare (Simnett 2003). The location is in the high corona. If this is correct, then we might consider that the ^{3}He is also accelerated in the same way.

7.3. Propagation

It is known that the enhancement in the ^{3}He/^{4}He ratio is not correlated with the intensity of the electron event at 1 AU (Ho et al. 2001). There are very many more radio type III bursts than detected impulsive electron events at the Earth. On the assumption that a type III radio burst is generated by a beam of electrons moving out through the corona into interplanetary space, then this merely shows that the spatial extent of the electron emission is quite small. Impulsive electron events seen near Earth rarely show dropouts in intensity which would indicate that the observing spacecraft has lost the magnetic connection to the source. As the near-relativistic impulsive electron events are short-lived, say typically around an hour, then the lack of dropouts in the observed intensity suggest that the spatial extent of the emission is at least (360° × (1 h)/(27 × 24 h), or about 0.5 degrees. However, the propagation speed of the ^{3}He nuclei is an order of magnitude lower that the electrons, and it is observed (Mazur et al. 2000) that such events show frequent dropouts.

8. Conclusions

We start by summarising the key facts that are fundamental to our model.

- Impulsive electron events are the most common solar particle event, occurring many times a day (Lin 1985).
- For many events the energy spectrum, which may extend as an unbroken power law down to 2 keV (Potter et al. 1980) places the acceleration site in the high corona.
- These events are largely uncorrelated with low coronal phenomena.
- ^{3}He events are strongly associated with impulsive electron events (Reames et al. 1985).
- The ^{3}He event fluence appears to have an upper limit (Ho et al. 2005).

The last of these facts provides a crucial indicator as to the location of the acceleration, as it must be in a region of with a finite amount of material. Thus a ^{3}He event in general accelerates perhaps all the ^{3}He in the source region (Roth & Temerin 1997).

The acceleration accompanying a major flare does not suffer from a limitation in the amount of available material as the chromosphere is a semi-infinite reservoir. The fact that major flares do not accelerate much ^{3}He indicates that the acceleration mechanism must be different to that occurring in the high corona. Thus we have the following situation:

$$^3\mathrm{He}/^4\mathrm{He} = \mathrm{A}^3\mathrm{He_c}/^4\mathrm{He_c} + \mathrm{B}^3\mathrm{He_f}/^4\mathrm{He_f}.$$

The subscripts c and f refer to the coronal (c) and flare (f) outputs, and A and B represent the fractions of the two acceleration processes contributing to a given event. As A and B are free parameters a wide range of ^{3}He/^{4}He ratios is possible.

We believe that one should not attach too much importance to associations of ^{3}He events with low coronal phenomena as these at best are chance associations, for which the high coronal acceleration is not relevant.

The detection of ^{3}He events at energies above 15 MeV/nuc is well established (Torsti et al. 2002, 2003a,b), but rare. We suggest that the accelerated particles from the high corona that do not get injected into the interplanetary medium act as a seed population for the flare, which we emphasize does not favour ^{3}He. Once the ^{3}He seed population is exhausted, then the flare accelerator only has the chromspheric plasma to work on. If the flare stops just as the ^{3}He seed population is exhausted then the energetic particle population will be ^{3}He-rich, but with a spectrum which extends to high energy. We assume that there will be a distribution of flare events, with most of them producing populations such as shown in Figs. 11 and 12.

Our proposal that the ^{3}He nuclei seen in solar energetic particle events is accelerated in the very high corona is supported by the following:

(1) The huge variation in the ^{3}He/^{4}He ratio observed in different events, covering a range of 10^4 to 10^5, can only be explained by two separate sources, one of which selectively energises all the ^{3}He nuclei in the acceleration region.
(2) The result of Ho et al. (2005), that there is a maximum fluence in any ^{3}He event, naturally follows from (1).

(3) The fact that the ^{3}He differential energy spectrum is quite different to that of ^{4}He, leading to an energy dependent ^{3}He/^{4}He ratio (Mason et al. 2002), also follows from (1).
(4) The typical association of the ^{3}He-rich events with impulsive near-relativistic events is consistent with a high coronal origin.
(5) ^{3}He events which occur in solar wind dwells, associated with coronal holes and a magnetically quite interplanetary medium, cannot originate in flares.
(6) Events such as those illustrated in Fig. 12 show that the acceleration process runs out of ^{3}He while continuing to accelerate ^{4}He.
(7) The physical parameters in the high corona are broadly consistent with those required by the resonance acceleration models discussed above.

The most significant conclusion from our study is the following. Wave-particle interactions in the high corona, probably stimulated by discrete magnetic reconnection events, are occurring quasi-continuously and resonantly accelerate ^{3}He, electrons, and heavy nuclei to energies around an MeV/nuc. There is likely to be a spectrum of magnitudes of these events. It is reasonable to suppose that approximately equal numbers of accelerated particles are emitted into the interplanetary medium as remain trapped in the corona.

The clearest indication of coronal activity comes from the impulsive electron events, primarily because the observations are at 1 AU and the electrons cover this distance in tens of minutes, compared to hours for particles in the MeV/nuc region. Any nuclei emitted at the same time may not appear as discrete events at 1 AU but contribute to a generally enhanced background. However, sometimes the ^{3}He has a favourable connection to the observer, leading to events such as those shown in Fig. 13.

The coronal population that slowly builds up may do two things. It could be released impulsively into the interplanetary medium at the time of a reconnection event that opens up the coronal magnetic field more than usual. At the same time some of the output could be dumped into an active region about to flare, where it may provide energetic seed particles for further acceleration in the active region. Our conclusions are directly relevant to the topic of energetic particle acceleration in flares.

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References

Bastian, T. S., Pick, M., Kerdraon, A., et al. 2001, ApJ, 558, L65
Cliver, E. W., & Kahler, S. W. 1991, ApJ, 366, L91
Dayeh, M. A. H., Desai, M. I., Dwyer, J. R., et al. 2008, ApJ, 693, 1588
Desai, M. I., Mason, G. M., Mazur, J. E., & Dwyer, J. R. 2006, ApJ, 645, L81
Fisk, L. A. 1978, ApJ, 224, 1048
Gold, R. E., Krimigis, S. M., Hawkins, S. E., III, et al. 1998, Space Sci. Rev., 86, 541
Gloeckler, G., & Geiss, J. 1998, Space Sci. Rev., 84, 275
Hseih, K. C., & Simpson, J. A. 1970, ApJ, 162, L191
Ho, G. C., Roelof, E. C., Hawkins, S. E., III, et al. 2001, ApJ, 552, 863
Ho, G. C., Roelof, E. C., Mason, G. M., et al. 2003, Adv. Space Res., 32, 2679
Ho, G. C., Roelof, E. C., & Mason, G. M. 2005, ApJ, 621, L141
Ho, G. C., Mason, G. M., & Roelof, E. C. 2007, AGU Fall Meeting, Paper SH53B-04
Ho, G. C., Lario, D., Decker, R. B., et al. 2008, Transient Shocks and Associated Energetic Particle Distributions Observed by ACE During Cycle 23, in Particle Acceleration and Transport in the Heliosphere and Beyond, American Institute of Physics, CP 1039, ed. G. Li, et al., 184
Kahler, S. W., Reames, D. V., & Sheeley, N. R., Jr. 2001, ApJ, 562, 558
Lin, R. P. 1985, Sol. Phys., 100, 537
Liu, S., Petrosian, V., & Mason, G. M. 2006, ApJ, 636, 462
Mason, G. M. 2007, Space Sci. Rev., 130, 231
Mason, G. M., Gold, R. E., Krimigis, S. M., et al. 1998, Space Sc., Rev., 86, 409
Mason, G. M., Mazur, J. E., & Dwyer, J. R. 1999, ApJ, 525, L133
Mason, G. M., Wiedenbeck, M. E., Miller, J. A., et al. 2002, ApJ, 574, 1039
Mason, G. M., Mazur, J. E., Dwyer, J. R., et al. 2004, ApJ, 606, 555
Mazur, J. E., Mason, G. M., & Dwyer, J. R. 2000, ApJ, 532, L79
Miller, J. A., & Vinas, A. F. 1993, ApJ, 412, 386
Nolte, J. T., & Roelof, E. C. 1973, Sol. Phys., 33, 241
Petrosian, V., Jiang, Y. W., Liu, S., et al. 2009, ApJ, 701, 1
Petschek, H. 1964, Magnetic Field Annihilation, in The Physics of Solar Flares, ed. W. N. Hess, NASA SP-50, 425
Pick, M., Mason, G. M., Wang, Y.-M., et al. 2006, ApJ, 648, 1247
Potter, D. W., Lin, R. P., & Anderson, K. A. 1980, ApJ, 235, L97
Reames, D. V. 1995, Rev. Geophys., 33, 585
Reames, D. V. 1999, Space Sci. Rev., 90, 413
Reames, D. V. 2000, ApJ, 540, L111
Reames, D. V., von Rosenvinge, T. T., & Lin, R. P. 1985, ApJ, 292, 716
Reames, D. V., Dennis, B. R., Stone, R. G., et al. 1988, ApJ, 327, 998
Roth, I., & Temerin, M. 1997, ApJ, 477, 940
Simnett, G. M. 2003, Sol. Phys., 213, 287
Simnett, G. M. 2004, A&A, 416, 759
Simnett, G. M. 2005, J. Geophys. Res., 110, A09S01
Simnett, G. M. 2006, A&A, 445, 715
Simnett, G. M., Sakai, J.-I., & Forsyth, R. J. 2005, A&A, 440, 759
Temerin, M., & Roth, I. 1992, ApJ, 391, L105
Temerin, M., & Roth, I. 1996, Selective Enrichment of Energetic Ions in Impulsive Flares, High Energy Solar Physics, ed. R. Ramaty, N. Mandzhavidze, & X. M. Hua (New York: AIP), AIP Conf. Proc., 374, 435
Torsti, J., Kocharov, L., Laivola, J., et al. 2002, ApJ, 573, L59
Torsti, J., Laivola, J., & Kocharov, L. 2003a, A&A, 408, L1
Torsti, J., Kocharov, L., & Laivola, J. 2003b, Sol. Phys., 214, 177
Wang, L., Lin, R. P., Krucker, S., & Mason, G. M. 2005, A Study of the Solar Injection for Eleven Impulsive Electron/^{3}He-rich SEP Events, Solar Wind 11 – SOHO-16, ed. B. Fleck, & T. H. Zurbuchen, Noordwijk, The Netherlands, ESA Conf. Proc., SP-592, 457
Wang, Y.-M., Pick, M., & Mason, G. M. 2006, ApJ, 639, 495
Wiedenbeck, M. E., Mason, G. M., Christian, E. R., et al. 2003, How Common is Energetic ^{3}He in the Inner Heliosphere? Solar Wind 10, ed. M. Velli, R. Bruno, & F. Malara, Melville, New York, AIP Conf. Proc., 679, 652