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Energetic Charged Particles in the Heliosphere from 1-120 AU Measured by the Voyager Spacecraft

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1. Introduction

For nearly 35 years the Voyager Spacecraft have been pursuing their epic journey to the boundaries of the heliosphere and interstellar (IS) space beyond. The remarkable observations of Jupiter, Saturn, Uranus and Neptune and their moons by Voyager are now long past. The observations of the giant bubble produced in the interstellar plasma by the outward flowing solar wind are still continuing however and are, in fact, building in excitement as the Voyagers cross or approach important boundaries between our local heliosphere and interstellar space. At the end of 2004, V1 crossed the heliospheric termination shock (HTS) at a distance of 94 AU from the Sun at a location of ~33° North. This shock is produced at a point where the outward moving solar plasma pressure is balanced by that of the interstellar medium including the magnetic (B) field. V2 crossed the HTS in August, 2007, at a distance of 84 AU at a location of ~25° South. This North-South asymmetry in the distance to the HTS (Stone, et al., 2008) has been determined to be due to the direction of the interstellar magnetic field. Its magnitude is estimated to be 4-5 μG or even larger, in contrast to pre-Voyager estimates of only 2-3 μG. The direction of this field is also determined for the 1st time and is such that it pushes in on the South hemisphere of the heliosphere; the B field making an angle ~40° with the local equator and creating a very distorted and asymmetric heliosphere in the North-South dimension (Opher, 2009).

Beyond the HTS is a region called the heliosheath. This region is believed to extend to a distance ~1.5 times the distance to the HTS and may have further North-South asymmetries. It is a very turbulent region where considerable energetic (≥ 1 MeV) particle acceleration occurs. Near its outermost boundary the wavy heliospheric current sheet, which changes in polarity every 11 years, bends back across the polar regions creating a long heliospheric tail, much like that of the Earth's magnetosphere. The outer boundary of the heliosheath is the heliopause (HP), a surface discontinuity between the solar wind plasma and the local interstellar plasma.

In this paper we are interested in the ≥ 1 MeV charged particle environment of this overall region extending outward from the Sun to at least 120-150 AU. This study is based mainly on the results from the Cosmic Ray Science (CRS) experiment (Stone, et al., 1977). At 2012.0, Voyager 1, the outermost spacecraft is approaching 120 AU and V2 is at ~98 AU. A schematic side-on view of the heliosphere is shown in Figure 1 to give an overall view of the heliospheric dimensions and the location of V1 and V2.

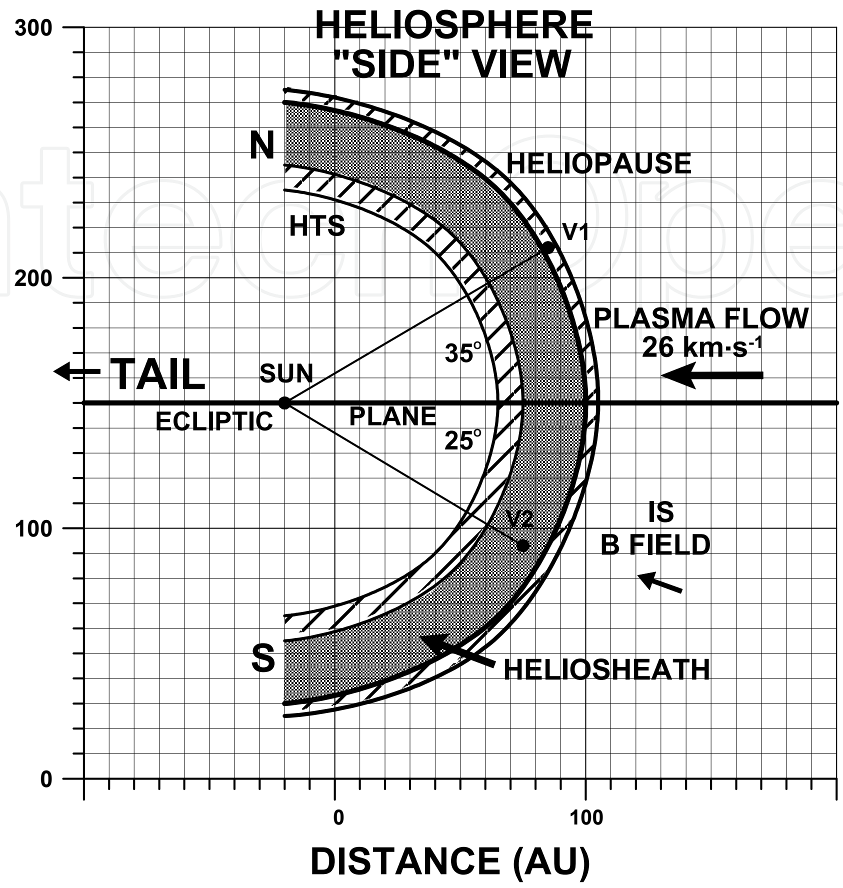

Fig. 1. Side on view of the solar wind dominated heliosphere showing the inner region, the HTS at about 90 AU, the heliosheath between 90-111 AU, and the outer transition region before the HP.

This environment includes galactic cosmic rays (nuclei and electrons) above a few MeV that enter the heliosphere from the galaxy where they populate interstellar space. Their intensity beyond the heliosphere is uncertain and their total energy density may even exceed that of the typical interstellar B fields and plasma. This cosmic ray component, which is the dominant one in the interplanetary region of the heliosphere, has a positive radial intensity gradient, indicating much larger intensities in interstellar space than at the Earth (for electrons, perhaps ~100 times).

There exist two other major components of energetic particles above ~1 MeV in the heliosphere region. These components are accelerated, either in the vicinity of the HTS (called Termination Shock Particles, TSP) or throughout the heliosheath and perhaps even near its outer transition region (called Anomalous Cosmic Rays, ACR). ACR's are only occasionally observed near the Earth. The details of these components have only been revealed as the Voyager approached and then crossed the HTS and explored the heliosheath region beyond.

The heliosheath is a giant region beyond the HTS of perhaps 20-40 AU in extent which is populated by protons, helium nuclei and oxygen nuclei with energies from ~1 MeV up to

~100 MeV (TSP and ACR). The power to accelerate these particles comes from the energy in the slowing down solar wind. This process may occur in several stages at various distances from the HTS to the outer boundary of the heliosheath. This region is bathed in massive intensities of these energetic particles, comparable to or larger than those found in the magnetospheres of the planets (e.g., the Earth, Jupiter, etc.) but in this case essentially surrounding the entire heliosphere outside of the HTS. This region, which will be described in detail in this paper, will certainly give pause to any space traveler whether they are leaving the solar system or coming to explore it, because of the severe radiation hazard over an extended period of time/distance that these energetic particles present.

2. Galactic cosmic rays

From its beginning over 70 years ago, one of the goals of the study of the very energetic galactic cosmic rays was to determine their intensity in the galaxy and also their origin. These goals have been hampered by the extensive modulation effects of the heliospheric plasma and magnetic fields. For the lowest energies these modulation effects are sufficient to reduce the intensities observed near the Earth by 10 to over 100 times from the interstellar intensities. Now at last the Voyagers spacecraft are pushing back this veil. In Figure 2 we show the total intensity of cosmic rays >70 MeV from the time of Voyager 1 launch in 1977 to the present time in late 2011, a time period of ~34 years. During this time the overall intensity of these particles has increased by a factor ~2.5 from that observed in 1977 which was a time of minimum modulation (highest intensity). The solar 11 year activity cycle is clearly evident in the data with successive intensity maximum in 1977, 1987, 1998 and 2009, at times of solar activity minima. The study of this solar modulation cycle as a function of radius is one of the ongoing areas of research for the Voyager Science Teams.

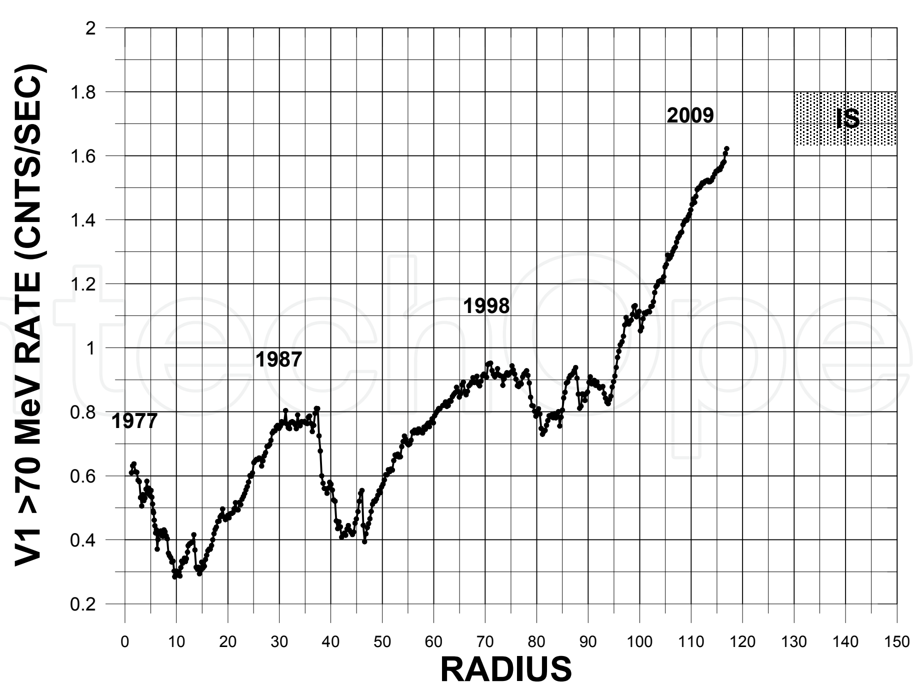

Fig. 2. Total intensity of cosmic rays >70 MeV at V1 from launch in 1977 to the present time. Times of maximum intensity (minimum solar activity) in the 11 year solar cycle are indicated. The estimated IS intensity is shown as a shaded region beyond 130 AU.

In late 2011, this integral intensity reached levels near the lower limit of the expected IS intensities based on models for propagation of cosmic ray nuclei in the galaxy (e.g., Webber and Higbie, 2009). However, as much as 10% of this integral intensity could be due to ACR's of energy >70 MeV and also to galactic cosmic ray electrons, not included in the models. With each passing AU this integral rate data becomes more and more constraining with regard to the IS energy density of these cosmic rays and their intensity and propagation in the galaxy.

In Figure 3 we present data for cosmic ray electrons of 6-14 MeV. These particles show a completely different radius vs. intensity profile than the nuclei. Near the Earth and out to perhaps ~40 AU these electrons are dominated by Jovian electrons. In fact, most of the electrons in this energy range measured near the Earth are not galactic electrons at all but are Jovian electrons propagating within the inner heliosphere (Ferreira, et al., 2001). These electrons peak at the time of the Jupiter encounter in 1979, with radiation levels that are dangerous to both man and the instruments (several instruments were affected). Beyond ~40 AU the electron intensities are dominated by galactic electrons, however. They show only weak modulation effects due to the solar 11 year cycle and at the time of the HTS crossing in late 2004 their intensity is within a factor ~2 of the intensity at the Earth after subtraction of the Jovian component at 1 AU.

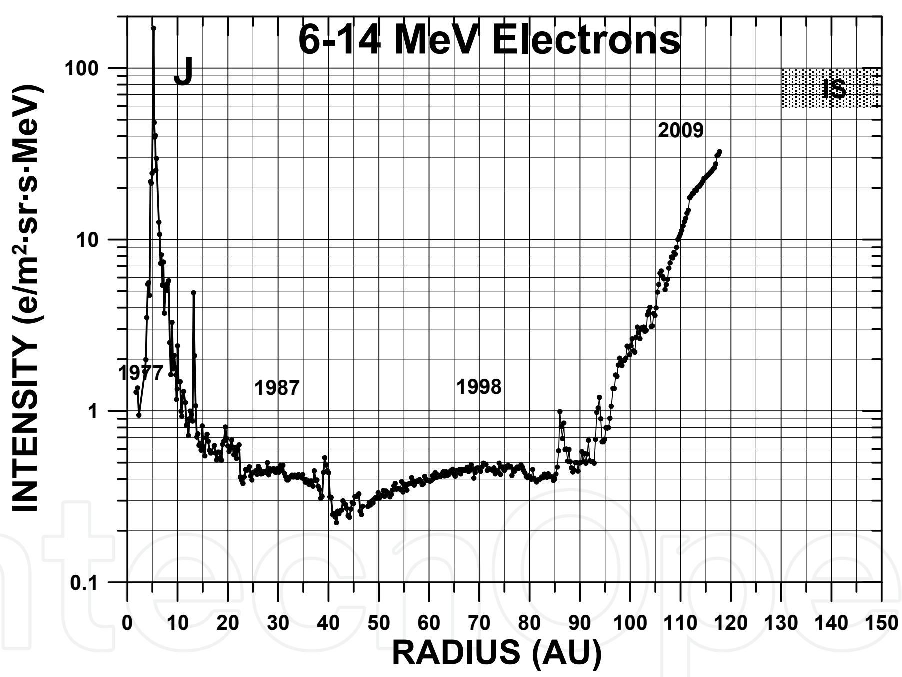

Fig. 3. Intensity of 6-14 MeV electrons at V1 from launch to the present time. The intensity peak at Jupiter encounter occurs in 1979. The intensity of these galactic electrons begins to increase only after crossing the HTS, reaching levels ~100 times those observed at the Earth. The estimated IS intensity is shown as a shaded region beyond 130 AU.

After crossing the HTS the 6-14 MeV electron intensity at V1 has risen continuously by a total factor ~60-80 by 2011.5, a period ~6.5 years. At 2009.7 and again at 2011.2 two sudden jumps in the electron intensity along with changes in their radial intensity gradient are observed. We believe that these times, which occur when V1 is at 111 AU and again at 116 AU, mark the times when V1 has passed significant structures in the outer heliosphere

(Webber, et al, 2011). These features may represent the fold back of the heliospheric wavy current sheet. This wavy current sheet has been observed by the Voyagers in the heliosphere inside the HTS and this layered structure may be carrying solar plasma and magnetic fields back to form the tail of the heliosphere (Florinski, 2011). This region is estimated to be 8-10 AU thick and its outer boundary may, in fact, be the heliopause, a 3-D surface separating the region of solar influence from the local interstellar medium (Washimi, et al., 2011). So in this scenario, V1 may be relatively close to observing the interstellar spectrum of these low energy electrons. It is seen in Figure 3 that the 6-14 MeV electron intensity at 2011.5 has almost reached the lower limits of the estimated IS electron intensities. These estimates are based on a combination of propagation models and the intensity of low frequency radio emission from these electrons in the galaxy. The overall uncertainty in the estimated IS electron spectrum is a factor ~2 (Webber and Higbie, 2008). So again with each AU that V1 travels outward, new limits are placed on the galactic propagation conditions at these low energies and also on the origin of these electrons and the distribution of their sources in the galaxy.

The changes in the spectrum of cosmic ray electrons at V1 as a function of time/radius are remarkable. These spectra from ~6-120 MeV are shown in Figure 4 from the time of the HTS crossing in one year intervals to 2011.5. As might be expected from Figure 3, the HTS spectrum/intensity is very similar to that at the Earth. Almost all of the intensity change occurs in these low energy electrons after the HTS crossing. The intensities increase by nearly a factor ~100 at the lowest energies and the spectrum quickly develops into a shape ~$E^{-1.7}$. This spectrum simply increases with increasing distance maintaining the same spectral exponent.

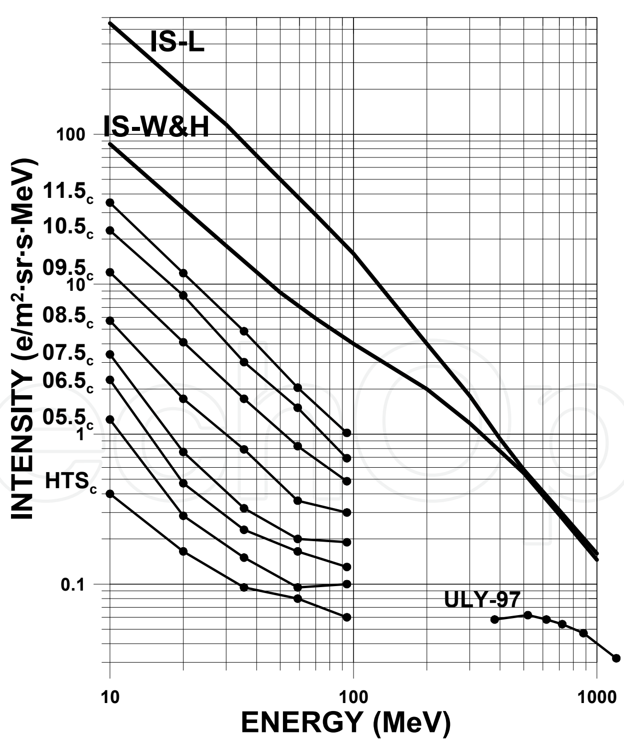

Fig. 4. Spectra of the galactic electron component from 10 MeV to 100 MeV. Voyager 1 measurements are shown at the time of the HTS crossing and yearly up to 2011.5 (117 AU). Estimated limits on the possible IS electron intensity are also shown. Ulysses measurements near the Earth at a time of minimum solar modulation are also shown at higher energies.

Two predictions of possible IS electron spectra are shown in the Figure. One is by Langner, et al., 2001, the other by Webber and Higbie, 2008. Both are based on the observed galactic radio synchrotron spectrum which results from the electrons propagating in the galactic magnetic fields, plus propagation/diffusion models. The electron spectrum measured at V1 at 117 AU is now only a factor ~2 below the lowest of these estimates. Measurements at energies above a few hundred MeV made at times of minimum modulation are shown from the Ulysses spacecraft. It is hoped that the new results from the PAMELA spacecraft which extend to lower energies, will help to constrain this higher energy part of the electron spectrum and overlap the Voyager measurements.

Next we present data for the individual nuclei, H, He and heavier nuclei such as C. Here we show the spectra of these nuclei measured by the CRS instrument on V1. The spectra for H nuclei are shown in Figure 5, for He nuclei in Figure 6 and for C nuclei in Figure 7. The spectra are shown for 3 times, 2009.5, 2010.5 and 2011.5 as V1 moves ever closer to the outer boundary of the heliosphere, at the rate of 3.6 AU/year. So these spectra are essentially snapshots of the intensities and spectra as these intensities approach the IS values. The H and He intensities are corrected for a background from ACR H and He nuclei which becomes important below ~100 MeV.

Also shown in all these figures are recently estimated IS intensities for these nuclei based on propagation models and estimated source spectra (Webber and Higbie, 2009). These estimates give the lowest intensities of the many historical estimates dating back over 30 years or more. It is seen that the intensities of all components, H, He and C are getting larger at the rate of 5-15% per year corresponding to radial distances of 110.3, 114.0 and 117.5 AU, but are still below these latest IS estimates.

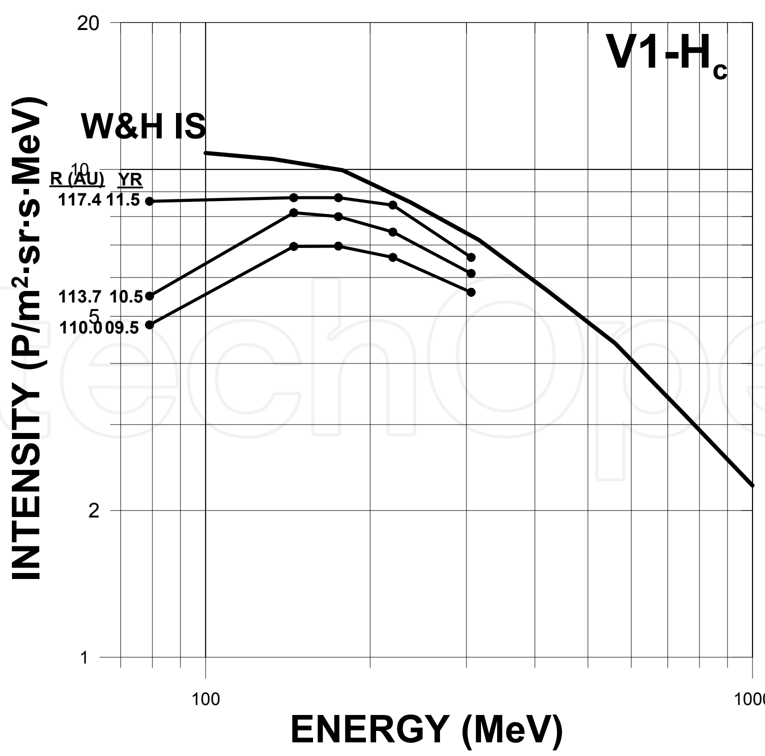

Fig. 5. Energy spectra of H nuclei measured at V1 at 2009.5, 2010.5 and 2011.5 (corrected for ACR background). Estimated IS spectrum for H is shown by a solid line.

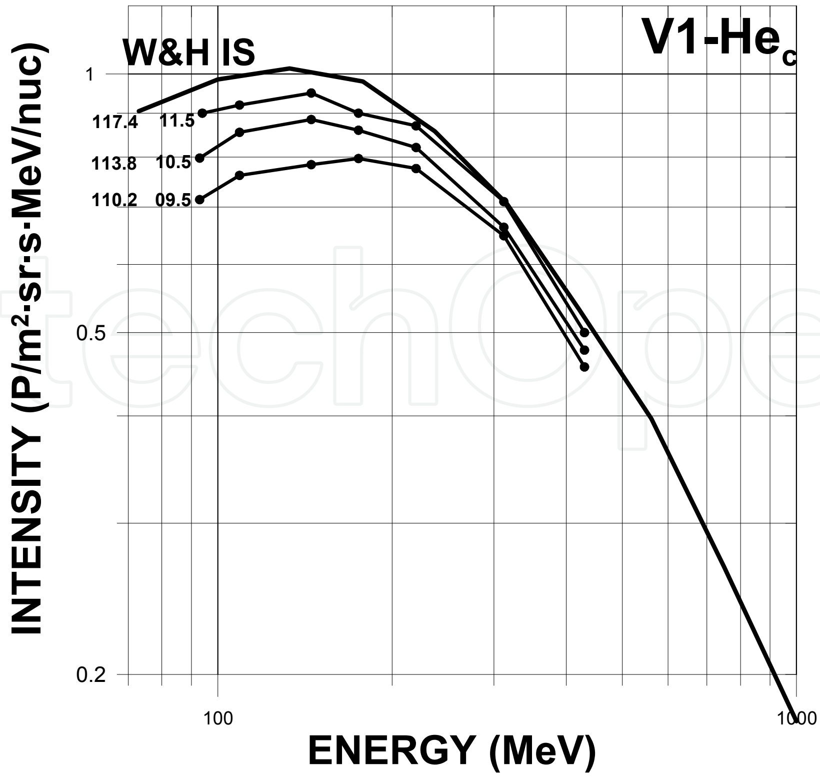

Fig. 6. Energy spectra of He nuclei measured at V1 at 2009.5, 2010.5 and 2011.5 (corrected for ACR background). Estimated IS spectrum for He is shown by a solid line.

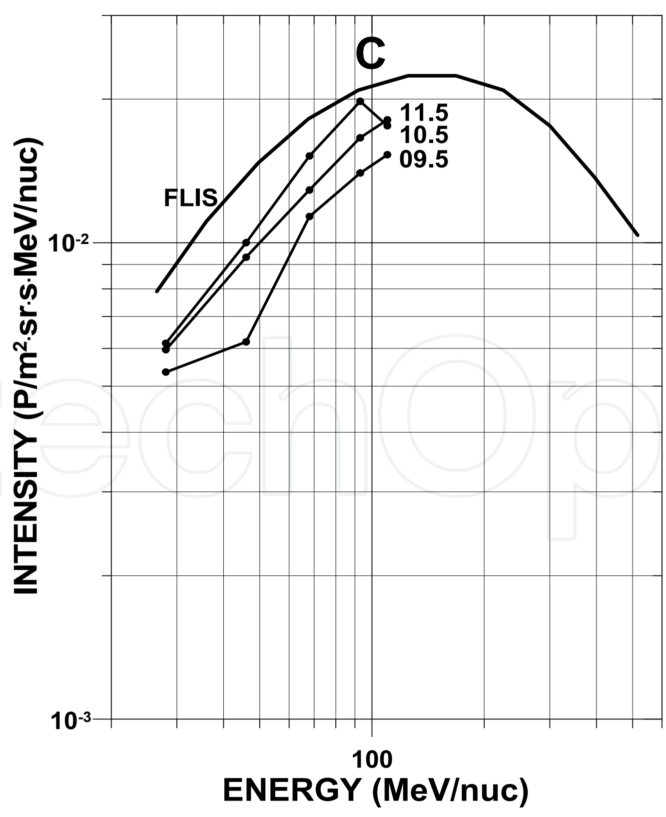

Fig. 7. Energy spectra of C nuclei measured at V1 at 2009.5, 2010.5 and 2011.5 (no correction for ACR needed). Estimated IS spectrum for C is shown by a solid line.

Using a simple "force field like" model which is commonly used to describe this solar modulation (e.g., Gleeson and Axford, 1968) and starting with the IS spectra given in Figures 5, 6 and 7, we find that a modulation parameter ϕ=53 MV fits the H data at 2009.5, a parameter = 39 MV fits the 2010.5 data and a parameter = 26 MV fits the 2011.5 data. The parameters that fit the He data are 47, 33 and 20 MV respectively. The spectra of all nuclei should be fit by the same value of the modulation parameter for each year. The slightly lower values of this modulation parameter for He relative to H could be explained by an increase in the IS He ~+3% relative to H.

As a point of reference the value of the modulation parameter required to reproduce the spectra of H and He nuclei that are observed at the Earth at the times of minimum modulation is ~400 MV, the same for both H and He. So the "amount" of modulation necessary to reproduce the H and He spectra observed at 2011.5 (117.5 AU), (which is between 20 and 26 MV), is 5-7% of that required to reproduce the spectra at the Earth. This data suggests that, at about 5-7 AU beyond the V1 location of 117.5 AU at 2011.5, the estimated IS spectrum will be reproduced by Voyager measurements at the current rate of intensity increase, e.g., the solar modulation will go to zero.

For C nuclei the spectrum can be measured from ~20-120 MeV/nuc using current analysis procedures. Fortunately this is the most interesting energy range, just below the peak in the differential spectrum. In the energy range below ~100 MeV/nuc the models used to describe the solar modulation predict a spectrum that is proportional to E, independent of the exact shape of the IS spectrum, as long as the modulation is "significant". In Figure 7 we note that the C spectrum at all times is very closely ~E and the "apparent" modulation is small as well.

Does this mean that the energy spectrum at V1 is close to the true IS spectrum at these energies or is the solar modulation larger at lower energies than that determined from the H and He data at higher energies so that, in fact, the modulation is producing the ~E spectrum? At ~100 MeV/nuc where the LIS spectrum can be calculated with reasonable accuracy (±10%) the apparent modulation for C (the value of ϕ) is ~45 MV at 2010.5 and ~27 MV at 2011.5, consistent with the modulation derived from the H and He spectra. So at ~100 MeV/nuc there is consistency between the relative IS H, He and C intensities and also consistency between the apparent solar modulations for these three components.

The ratio of IS He/C intensities at ~100 MeV/nuc is a critical parameter for any galactic propagation/source model for cosmic rays. This is so because the energy loss by ionization in the galaxy is large and becoming dominant at this energy and this E loss parameter is ~Z^2. The measured value for this ratio at V1 at 2011.5 is 46.5±3, a dramatic improvement over values for this ratio being used at the present time which have uncertainties of ±50% (e.g., Putze, Maurin and Donato, 2011). Note that small levels of solar modulation will not change this ratio because of the similar spectra and the identical A/Z ratio = 2.0 of these nuclei. These are the most important factors in the modulation calculation at these energies.

3. The anomalous components

ACR Oxygen nuclei were first discovered in 1974 by instruments on the Pioneer spacecraft just after their launch (McDonald, et al., 1974). This result was confirmed by the CRS instruments on Voyager. These particles were recognized as anomalous because of an unexpected upturn in the spectrum of low energy galactic O nuclei. In subsequent years it has been found that the ACR O component has a source spectrum between ~E^{-2} - E^{-3}, with the spectral index increasing with increasing energy at energies from a few MeV up to as high as 50 MeV/nuc. The time history of these nuclei from 1977 to the present as measured by V1 is shown in Figure 8. It can be seen that these nuclei almost vanished in 1980-81 at a time of the 11 year maximum in solar modulation. But the intensity recovered to still higher intensities at the next modulation minimum in 1987.

Theories for their origin have centered on the acceleration of IS neutral atoms, first ionized in the outer heliosphere and then accelerated (Fisk, Kozlovsky and Ramaty, 1974). But the apparent acceleration region has moved outward as the intensity has continued to increase with increasing radius. The intensity showed no sudden increase at the HTS, considered to be one of the possible acceleration locations. In fact, the intensity has continued to increase throughout the heliosheath, but now seems to have reached a maximum in 2009-2010, at about 110 AU, ~15 AU beyond the HTS. This distance of ~110 AU corresponds to the time at which the first of several sudden electron intensity increases, as was noted earlier, was seen at V1. A jump in magnetic field strength and a change of polarity of the field observed at this time (Burlaga and Ness, 2010) provides additional evidence that V1 crossed a significant structure at this time, perhaps moving into the 1st of several layers in a transition zone from solar dominated to interstellar dominated plasma conditions. This is also the time when the radial component of the solar wind speed becomes ~zero (Krimigis, et al., 2011).

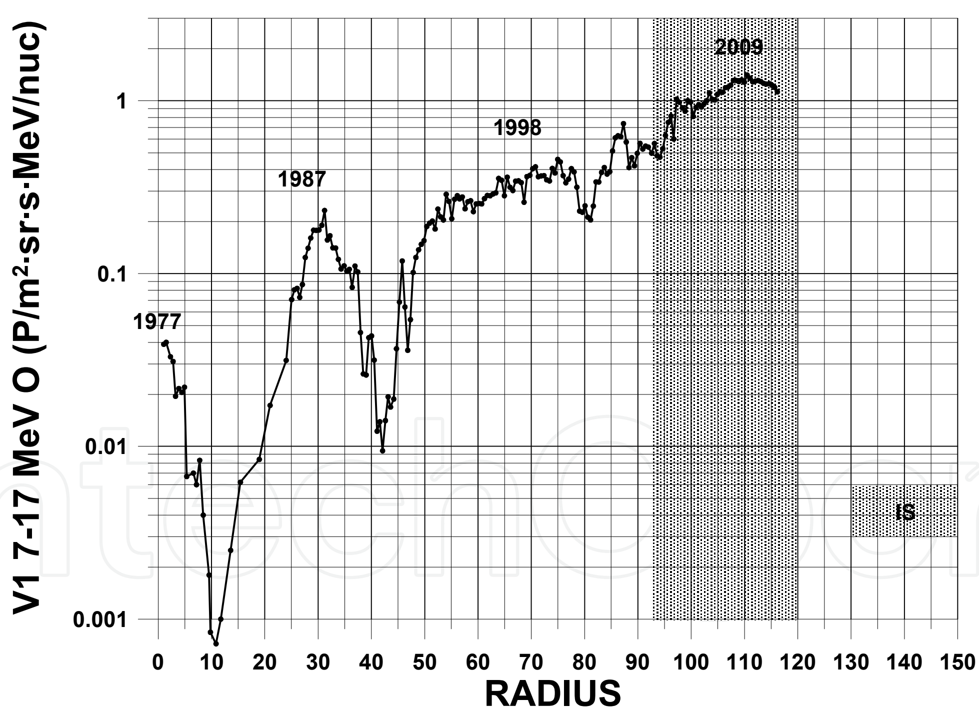

Fig. 8. Intensity of 7-17 MeV ACR-O nuclei from launch to the present time. The solar 11 year cycle and the extreme modulation of these ACR at times of maximum solar activity in 1980-1982 and 1990-1991 are evident.

At the time of maximum in 2009-2010 at between 110-115 AU, the intensity of 7-17 MeV/nuc ACR-O nuclei was ~50 times the maximum intensity observed at the Earth. The IS intensity of these low energy particles is completely unknown. A galactic component as part of the spectrum of cosmic ray O nuclei would be a factor of at least 500 below the peak intensity observed in the heliosheath (see Figure 8).

We next examine the other major components of ACR, the H and He nuclei, concentrating here on H nuclei. All of the ACR nuclei have very similar spectra, ~E^{-2} at the lowest energies below ~10-20 MeV, and steepening to E^{-3} at the higher energies and extending up to ~100 MeV for H (for more spectral information see Cummings, et al., 2011). The abundance of H nuclei is ~10 times that of He at a fixed energy (below ~20 MeV). We consider the highest energies first and then work down to lower energies.

Figure 9 presents the time history of 27-69 MeV H nuclei. At these energies the ACR spectrum sits atop the galactic spectrum of H nuclei. The estimated galactic H nuclei intensities at times of minimum modulation are shown as large dots which are only slightly below the total H nuclei intensities measured in the inner heliosphere. Even at the times of intensity maxima in 1977 and 1987, it was not clear that an anomalous H component was present. The existence of this component was clearly demonstrated at the time of the next maximum intensity in 1998 when the effects of solar modulation between V1 and the source became much less as V1 moved outward toward the source region. It is now recognized that H nuclei are the dominant component of ACR in the heliosheath energetically and intensity wise. At the time of peak intensity at ~110 AU, ACR H at an average energy ~50 MeV was ~20 times greater than the galactic H intensity at the same energy.

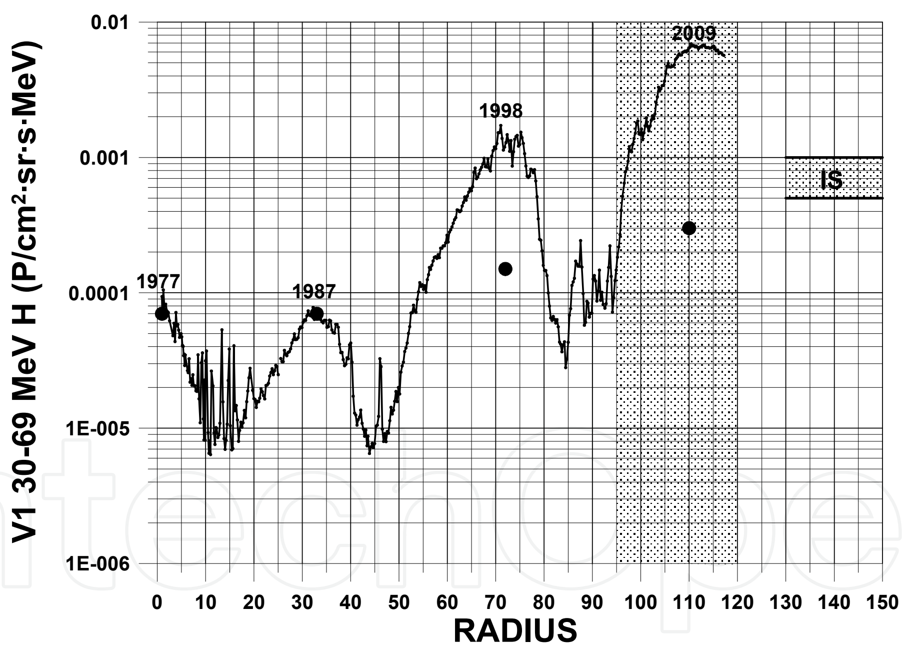

Fig. 9. Intensity of 27-69 MeV H nuclei, including both ACR and GCR from launch to the present time. Estimated galactic H nuclei contribution is shown as big dots at times of maximum intensity. The estimated IS intensity of galactic H nuclei at this energy is shown as a shaded region beyond 130 AU.

Note that there are several spikes in the intensity-time profile of 27-69 MeV H nuclei between 8-20 AU. This is a time of maximum solar activity between 1980-1982 and these spikes are the high energy tips of individual solar/interplanetary cosmic ray acceleration events propagating outward in the heliosphere.

In Figure 10 we present the time history of 10-21.5 MeV H nuclei, a factor ~3 lower in energy. This figure looks much like the higher energy H nuclei in Figure 9. At this lower energy the presence of ACR H again does not stand out in the inner heliosphere relative to an even lower intensity galactic component (the galactic intensity is scaled ~E). ACR-H nuclei become obvious again only at the time of the 1998 intensity maximum. The intensity maximum for these particles is observed beyond the HTS at between 110-115 AU and at that distance the intensity is ~100 times the estimated galactic intensity at this same energy.

Note the increased presence of spikes in the intensity-time profile between 8-20 AU in the 10-21.5 MeV channel. Again these spikes are the medium energy part of the spectra of individual solar/interplanetary cosmic ray acceleration events propagating outward through the heliosphere. The large spike at ~46 AU (at 1991.72) at V1 was from a solar (CME) event at 1991.42 at the Earth. The time difference of 0.30 year represents the propagation time of this disturbance (shock) between the Earth and V1.

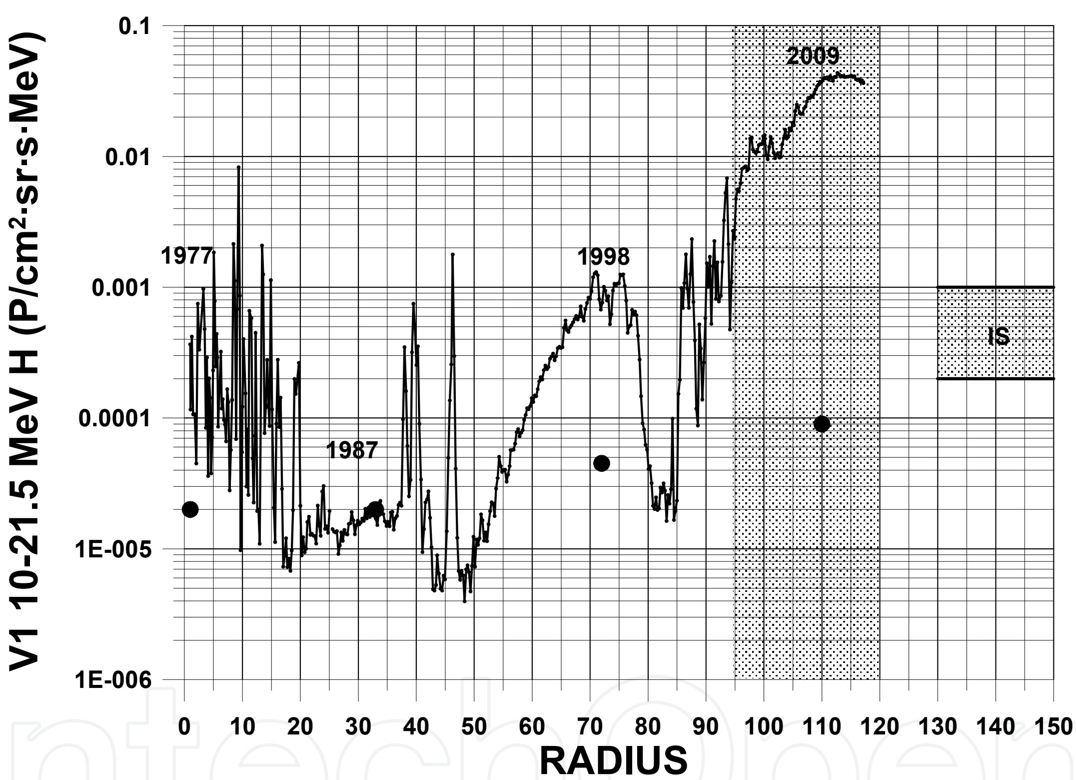

Fig. 10. Intensity of 10-21.5 MeV H nuclei, including both ACR/TSP and GCR and solar/interplanetary protons from launch to the present time. Estimated galactic contribution is shown as big dots at times of maximum intensity. The estimated IS intensity of galactic H nuclei in this energy range is shown as a shaded region beyond 130 AU. The presence of solar/interplanetary accelerated nuclei is an almost continuous excess intensity from launch to ~20 AU (1978-1982).

In Figure 11 we present the time history of 3-8 MeV H nuclei, another factor ~3 lower in energy than Figure 10. At this energy there is again no strong evidence of an ACR H component or even a galactic component before the 1998 intensity maximum. Most of the intensity variations in this channel up to ~50 AU are due to individual solar/interplanetary cosmic ray acceleration events. In fact these events, on average, increase the intensity in this energy channel by a factor >100 over the intensity due to that from galactic cosmic rays alone. Many of these events produce intensities >10^3 times the background intensity even at distances ~20 AU or greater from the Sun.

The actual 3-8 MeV heliosheath ACR/TSP "component" makes it first appearance at V1 about 10 AU before this spacecraft reaches the HTS. The intensity increases before the HTS crossing in a complicated series of increases, some of which are periodic. After the HTS crossing the intensity continues to increase rapidly and more smoothly, reaching levels ~10 times those at the time of the HTS crossing itself. Again, the intensity peaks at between 110-115 AU at levels between 10^2-10^3 times those expected for the estimated galactic spectrum in IS space and a factor ~10^4 times the quiet time intensity observed by V1 as it left the Earth.

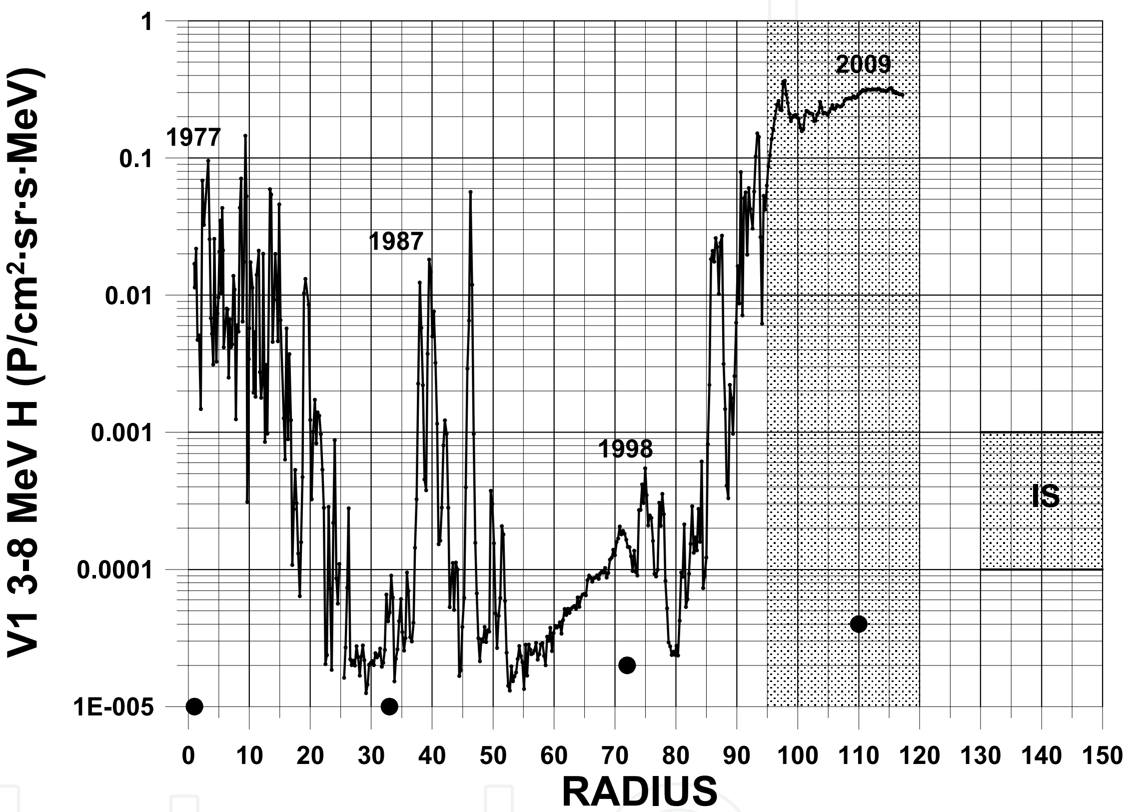

Fig. 11. The intensity of 3-8 MeV H nuclei from launch to the present time. These nuclei are mainly solar/interplanetary protons in the inner heliosphere during solar active periods and ACR/TSP H nuclei beyond ~50 AU, increasing rapidly just prior to the HTS and reaching an intensity maximum at ~110 AU, ~10^3 times a possible IS galactic component of H nuclei. Estimated galactic contribution is shown as big dots at times of maximum intensity. The estimated IS intensity of galactic H nuclei in this energy range is shown as a shaded region beyond 130 AU. The presence of solar/interplanetary accelerated nuclei increases the average intensity of 3-8 MeV H by a factor ~100 inside of 20 AU (1978-1982).

The final Figure, #12, shows the integral rate of all particles >0.5 MeV from launch to the present time. This rate is probably the best representation of the total radiation that would be received by an instrument or a person at that location. The large dots show the total rate that would be observed from galactic cosmic rays only at a time of minimum modulation. The solar 11 year modulation cycle is barely visible in the data. What are notable here again are the spikes of intensity observed in the inner heliosphere out to ~20 AU and beyond. As noted previously these are individual solar interplanetary acceleration events and they increase the average integral intensity by a factor 10-100 times the normal background level due to the galactic cosmic rays only.

The other feature in the >0.5 MeV data is the high intensity in the heliosheath, mainly due to TSP and ACR beginning, in fact, with discrete and large increases that begin to appear 5-10 AU prior to the HTS crossing. This intensity again peaks at a distance ~110-115 AU from the Sun.

The total integral intensities in the heliosheath are 10-20 times those expected from galactic cosmic rays which have an energy density ~1 eV/cm^3 in interstellar space.

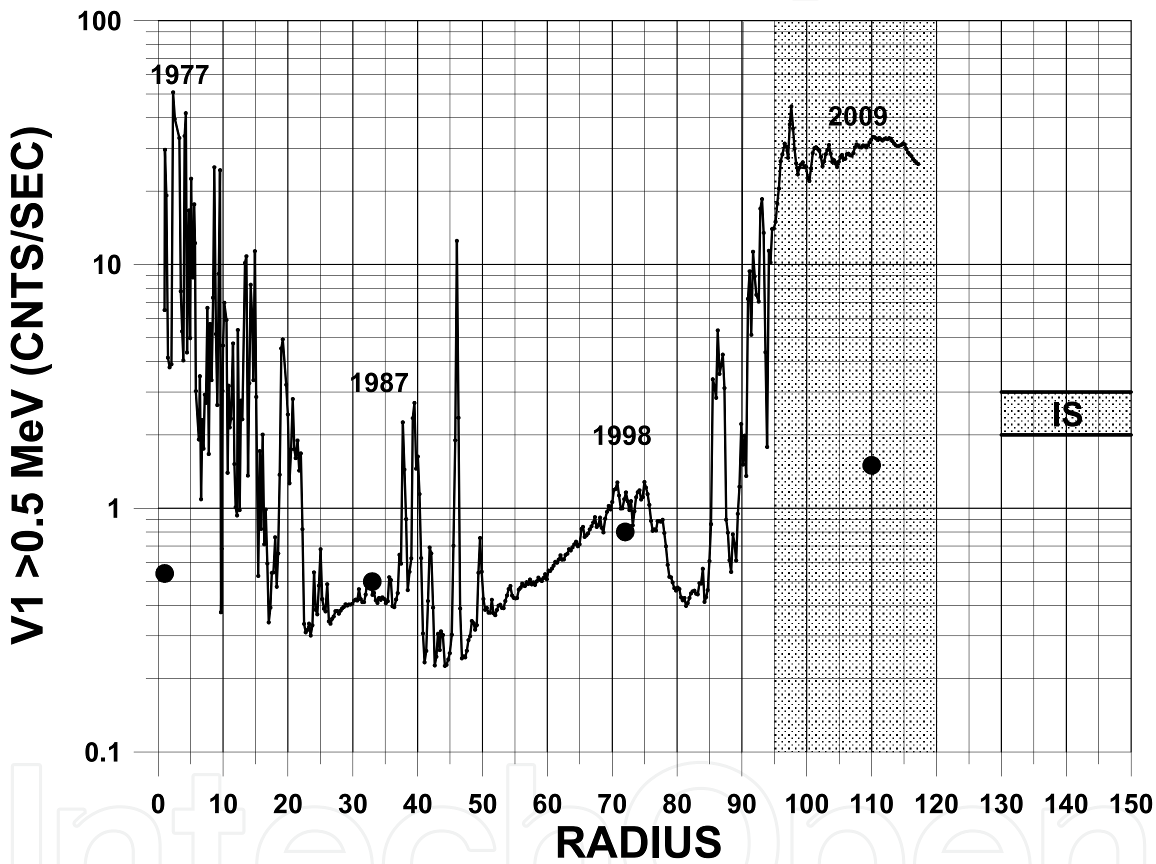

Fig. 12. The integral intensity of >0.5 MeV particles from launch to the present time. These particles again are mainly solar/interplanetary particles in the inner heliosphere and ACR/TSP in the outer heliosphere and in the heliosheath beyond the HTS. They increase to a maximum intensity at about 110 AU. The estimated galactic H nuclei contribution at times of minimum modulation is shown as big dots. The estimated IS (galactic) intensity of all H nuclei is shown as a shaded region beyond 130 AU.

4. Conclusions

The 34 year mission of the Voyagers to the outer heliosphere has led to nothing less than a complete reorganization of our understanding of the size and scope of the heliosphere surrounding the Sun and of the very considerable acceleration of particles within. This includes the global effects of the modulation process as the solar magnetic fields and plasma influence the energetic particles that enter this region from interstellar space beyond. The full extent of the reorganization of the modulation process is only just becoming apparent as this Voyager data is made available in articles such as this.

There is evidence that V1 (and maybe V2 as well) are nearing the outermost boundaries of the solar dominated heliosphere itself, thus lifting the veil that has existed and prevented access to the interstellar plasma, energetic particle intensities and the magnetic field. Already the intensities of the most important nuclei such as H, He and C, as well as the enigmatic electrons are approaching some of the lower and more recent estimates of the interstellar intensities at energies as low as ~100 MeV. In the next 3 years both V1 and V2 will travel a further 10 AU beyond their present locations of nearly 120 AU and 100 AU respectively. If in this time there is still no substantial evidence that we have reached full interstellar conditions, certainly the values and limits of key IS parameters such as the cosmic ray energy density, the magnetic field strength and indeed those parameters governing the origin and propagation of the great bulk of cosmic rays of energy ~1 GeV, or less, will be refined by an order of magnitude or more over the situation existing even today.

In the heliosphere itself, the most important result of the Voyager energetic particle studies has to be the observation of extraordinarily high intensities of energetic particles from 1-100 MeV in the outermost heliosphere. This includes both the large modulation effects observed between the inner and outer heliosphere and the massive intensity of MeV particles that is observed as the HTS is approached and the spacecraft enter the heliosheath beyond. The modulation effects, a factor of ~100 times or more at solar activity maxima, effectively shield the inner heliosphere from the source of these particles in the heliosheath while at the same time providing very sensitive tests of solar modulation theory. These tests will be more fully exploited as the V1 and V2 data are more fully disseminated.

The intensities of the 3-8 MeV ACR and TSP particles (H nuclei) in the heliosheath in the lower energy regime are perhaps 10^3 times the normal intensity of galactic particles at this energy. The same relative factor between ACR intensities and galactic intensities applies to ACR-He since the typical ACR H/He ratio (per nuc) is ~10, the same as the ratio for galactic cosmic rays. For ACR-O nuclei the H/O ratio at these low energies (per nuc) is ~300, compared to a ratio ~500 or more for galactic particles, so the ACR-O will make a relatively larger contribution. In terms of energy loss by ionization, which is ~Z^2, if the contribution to the ionization of the IS medium from ACR-H is 1.0, then ACR-He is ~0.5 and ACR-O is ~0.2.

The overall intensity and energy supply for the ACR (and TSP) components must ultimately come from the solar wind plasma and magnetic fields as the solar wind is brought to a stop first near the HTS and then throughout the heliosheath by the interstellar plasma and magnetic fields. The ultimate acceleration process and its location have yet to be identified for the ACR. This source always seems to be just "beyond" the V1 location. The recently identified intensity peak at between 110-115 AU in the heliosheath observed at the location of V1 seems to be a most important step in this identifying process. Of the many models that have been suggested for this acceleration process, the one that seems to best reproduce the Voyager intensity vs. radius profiles, in our opinion, is the model by Ferreira, Potgieter and Scherer, 2007 which incorporates both stochastic and diffusive acceleration (so called Fermi II acceleration) throughout the heliosheath region beyond the HTS. These processes operate with different effectiveness at different locations in the heliosheath depending on the value of the diffusion coefficient.

For the TSP, which are important below ~10 MeV near the HTS, a separate acceleration source near the HTS is apparent just from the intensity-time profiles of these few MeV particles at V1 and particularly at V2 as they cross the termination shock. This acceleration process may be enhanced by the interaction of strong interplanetary shocks with the HTS itself producing periodic intensity-time profiles that are multiples or sub-multiples of the solar 27 day rotation period driven by the heliospheric wavy current sheet.

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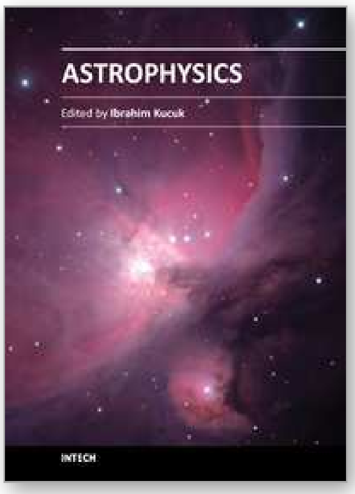

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